# ME571/Geol571 Advanced Topics

## Geology and Economics of Strategic and Critical Minerals

## Commodities—beryllium

Virginia T. McLemore

# ASSIGNMENT

- **NEXT WEEK (Feb 26) no class, REE March 5, 12**
- **Midterm due March 19, 2013 by e-mail ginger@nmbg.nmt.edu**
- Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806, http://canmin.geoscienceworld.org/content/46/4/779.full.pdf+html?sid=180ae325-acd5-4226-9a02-175f7a865e17
- Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., http://pubs.usgs.gov/sir/2010/5220/ (accessed 5/1/12).
- Mariano and Mariano, 2012, Rare earth mining and exploration in North America: Elements, v. 8, 369-376, http://elements.geoscienceworld.org/content/8/5/369.full.pdf+html?sid=605ebd04-9070-4994-9bce-b1cdd79f349d

# What is beryllium?

# What is beryllium?

- Beryllium
  - Average of 0.52 mg/kg in soil
  - Occurs as minerals, trace concentrations in other minerals

Beryllium metal

Beryllium ore

Beryllium oxide

Beryllium alloys

Beryllium is a rare metal with unique characteristics.

It is used as a pure metal or as an alloy with copper and aluminum.

Bertrandite and beryl pegmatite are the two most common beryllium ores.

# Beryllium

- 4th element on the periodic table
- 44th element in abundance
- Gemstone
- low density (1.85 grams/cubic centimeter)
- it has a very high melting point: 1,278° C
- resistance to creep, shear strength, tensile strength, comprehensive yield strength and just its fracture toughness

# Beryllium—Properties

- Low absorption cross-section with respect to thermal neutrons
- Light element
- Ability to withstand extreme heat
- Remain stable over a wide range of temperatures
- Function as an excellent thermal conductor
- Transparent to x-rays
- Light
- Non-sparking
- High heat capacity
- Stronger than steel
- In small amounts prevents metal fatigue failure in alloys with other metals

# Beryllium—Uses

- Electronic and electrical components
- Aerospace and defense applications
- Used as pure metal
- Mixed with other metals to form alloys
- Processed to form salts that dissolve in water
- Excellent refractory=processed to form oxides and ceramic materials
- Reflector of neutrons=application in nuclear reactors

# Beryllium—Uses

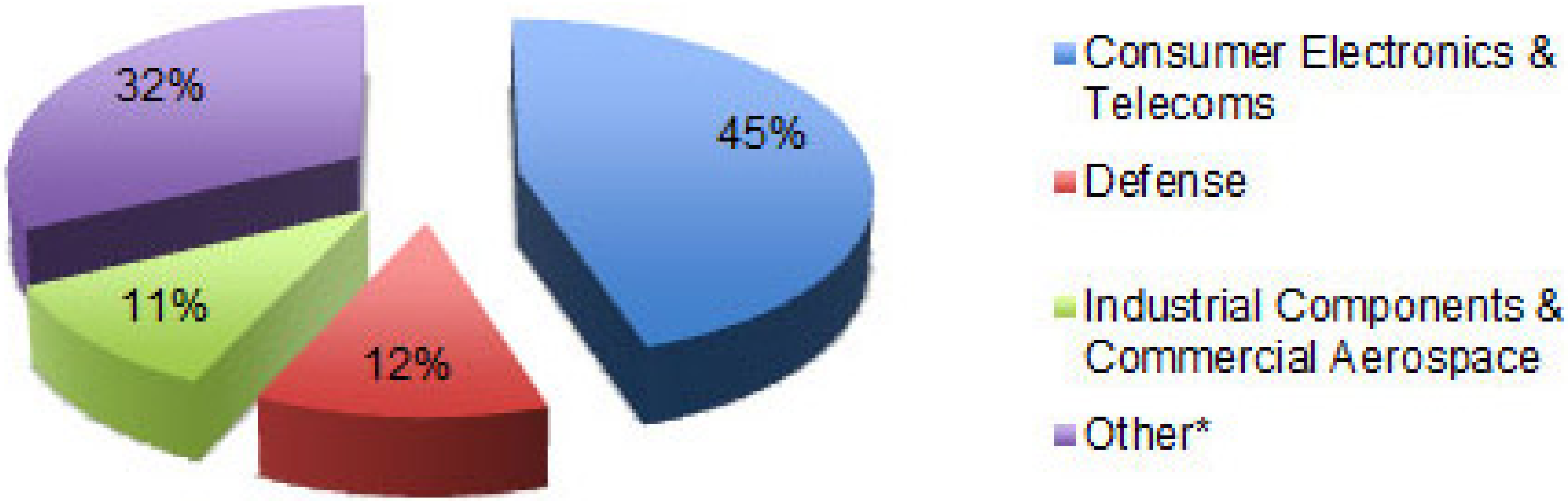
- Air bag sensors
- Ignition
- Power steering and electronic auto systems
- Fire extinguishers
- Sprinkler heads
- Pacemakers
- lasers
- Military electronic targeting and infrared countermeasure systems
- Circuits controlling electric windows in cars
- computer chip heat sinks
- Nuclear fuel
- Wind turbine components
- Golf club shafts
- Engine blocks
- Disc drives
- Wheel rims
- Cellular phones
- Home temperature controls
- Ceramics

View of the back of one of the 18 beryllium mirror segments for the James Webb Space Telescope. The ribs at the back of the mirror help to maintain the mirror's strength and ability to hold its shape under extreme conditions. The front of the mirror is completely smooth and coated in a thin film of gold. Photograph courtesy of the National Aeronautics and Space Administration.

The U.S. Air Force F-35 Lightning II Joint Strike Fighter and many other aerospace vehicles rely on electrical and mechanical components made of beryllium alloys.

USGS

Beryllium Use in the U.S. – 2011 (based on sales revenues)




Source: USGS *Appliances, automotive electronics, energy, medical devices and other applications

USGS

# Beryllium—Substitutions

- Be is used in applications in which its properties are crucial, so few substitutions for many applications
- Graphite
- Steel
- Titanium
- Aluminum nitride
- Phosphor bronze

# Beryllium—Production

Metric tons

USGS

| Salient Statistics—United States: | 2008 | 2009 | 2010 | 2011 | 2012[e] |
|---|---|---|---|---|---|
| Production, mine shipments[e] | 175 | 120 | 180 | 235 | 200 |
| Imports for consumption[1] | 70 | 24 | 271 | 92 | 106 |
| Exports[2] | 112 | 23 | 39 | 21 | 63 |
| Government stockpile releases[3] | 47 | 19 | 29 | 22 | ([4]) |
| Consumption: | | | | | |
| Apparent[5] | 218 | 170 | 456 | 333 | 220 |
| Reported, ore | 220 | 150 | 200 | 250 | 190 |
| Unit value, annual average, beryllium-copper master alloy, dollars per pound contained beryllium[6] | 159 | 154 | 228 | 203 | 209 |
| Stocks, ore, consumer, yearend | 60 | 30 | 15 | 10 | 30 |
| Net import reliance[7] as a percentage of apparent consumption | 20 | 29 | 61 | 29 | 10 |

# Beryllium—World Production
## Metric tons USGS

(Metric tons, gross weight)

| Country[3] | 2006 | 2007 | 2008 | 2009 | 2010[e] |
|---|---|---|---|---|---|
| China[e] | 500 | 500 | 500 | 500 | 550 |
| Madagascar[e, 4] | 12 | 12 | 12 | 12 | 12 |
| Mozambique | 16 | 31 | 8 | 45 | 45 |
| Portugal[e] | 5 | 5 | 5 | 5 | 5 |
| United States, mine shipments[5] | 3,830 | 3,810 | 4,410 | 3,030 | 4,460 |
| Total | 4,360 | 4,360 | 4,940 | 3,590 | 5,080 |

[e]Estimated.

[1]World totals, U.S. data, and estimated data are rounded to no more than three significant digits; may not add to totals shown.

[2]Table includes data available through August 11, 2011. Unless otherwise noted, figures represent beryl ore for the production of beryllium and exclude gem-quality beryl.

[3]In addition to the countries listed, Uganda produced beryl ore. Kazakhstan, Nigeria, and Russia may also have produced beryl ore, but information is inadequate to make reliable estimates of production. Other nations that produced gemstone beryl ore may also have produced some industrial beryl ore.

[4]Includes ornamental and industrial products.

[5]Includes bertrandite ore, calculated as equivalent to beryl containing 11% beryllium oxide.

Brazil ships beryl to Utah

# Beryllium—world production

metric tons

USGS

**World Mine Production and Reserves:**

| | Mine production[e] | |
|---|---|---|
| | **2011** | **2012** |
| United States | 235 | 200 |
| China[10] | 22 | 25 |
| Mozambique | 2 | 2 |
| Other countries | 1 | 1 |
| World total (rounded) | 260 | 230 |

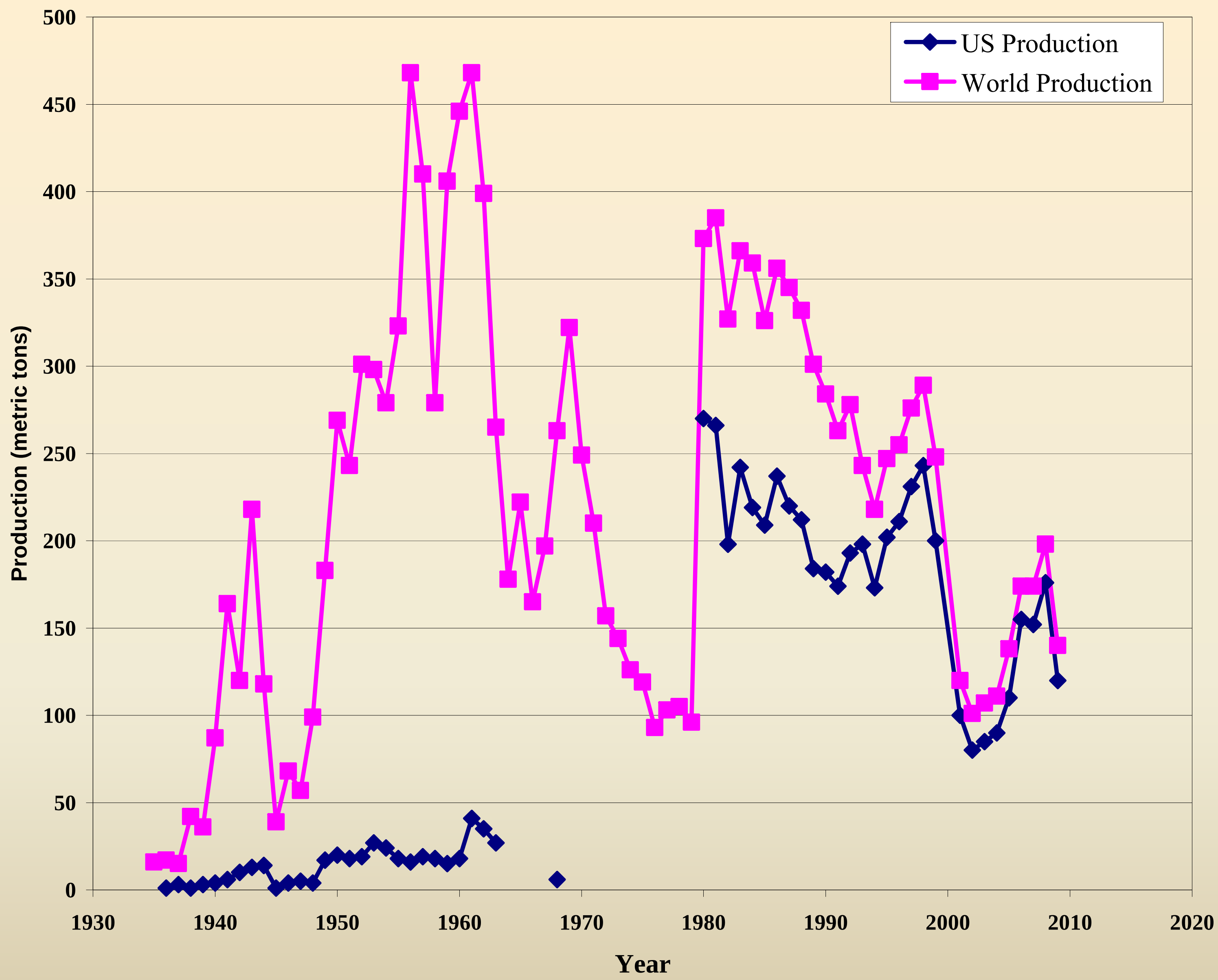
# Beryllium—resources

USGS

**Reserves**[9]

The United States has very little beryl that can be economically handsorted from pegmatite deposits. The Spor Mountain area in Utah, an epithermal deposit, contains a large bertrandite resource, which was being mined. Proven bertrandite reserves in Utah total about 15,200 tons of contained beryllium. World beryllium reserves are not sufficiently well delineated to report consistent figures for all countries.

**World Resources:** World identified resources of beryllium have been estimated to be more than 80,000 tons. About 65% of these resources is in nonpegmatite deposits in the United States—the Gold Hill and Spor Mountain areas in Utah and the Seward Peninsula area in Alaska account for most of the total.




World and U.S. Be production 1935-2009 (U.S. Geological Survey, 2009)

# Beryllium Market Structure

- Brush Resources is currently the sole US producer of beryllium concentrates.
- Spor Mountain and Hogs Back mines produce bertrandite.
- Processing plant at Delta, UT produces beryllium hydroxide from bertrandite and beryl for sale to beryllium markets.

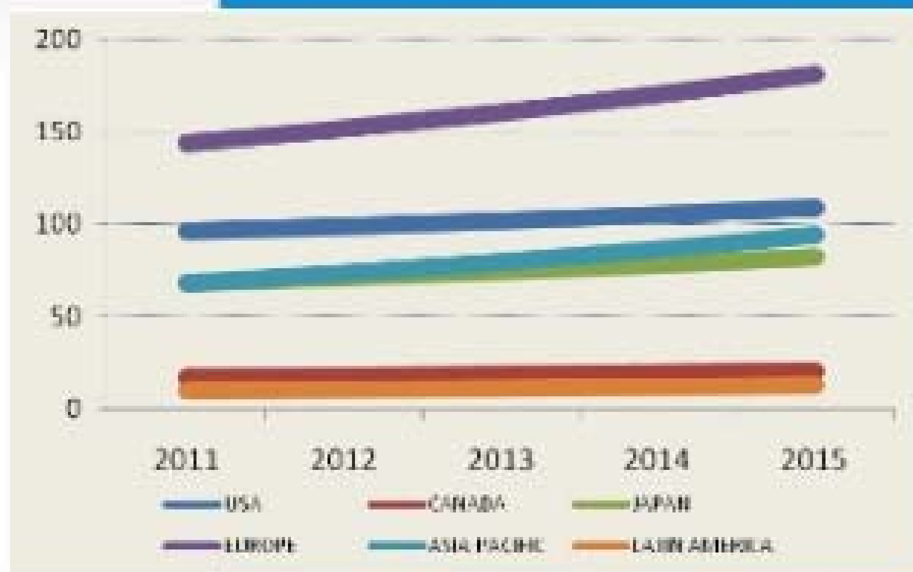
- Can you afford to ship product to Delta, UT at the price Brush will pay?
- Will Delta accept your product?

'Global Beryllium Demand to Reach 465 Metric Tons by 2015" Global Industry Analysts, Inc. 2010

## Growing Be supply/demand

Imbalance favors suppliers

- Only three primary sources globally (BW, Ulba, US gov't)
- No spot market
- Dramatic price rise (44%) between 2006 and 2008 (up to $500kg)
- High price has prevented wider use of Be
- One source (US Govt. stockpile) decreased availability 2008 / 2009




**WORLD BERYLLIUM CONSUMPTION**
**(METRIC TONS)**

*Source: Beryllium – A Global Strategic Business Report, Global Industry Analysts, Inc.*

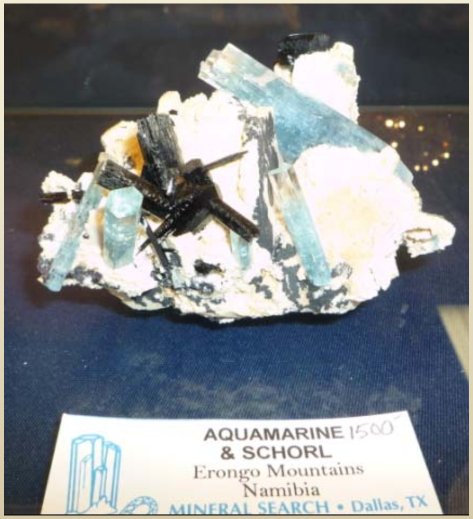
# Supply/Demand

- The uses for beryllium and thus the market are expanding.
- The Brush Resources operation has reserves sufficient to meet its needs for many years to come.
- Mine production is based on the amount of beryllium hydroxide that can be sold and thus varies from year to year.

# Beryllium—Mineralogy


# Gemstones

- Gems known to ancient man
  - Romans had emerald mines >2000 yrs ago in Egypt
- Emerald (green)
- Aquamarine (blue, gree)
- Chrysoberyl (golden beryl)=alexandrite
- Beryl
- Goshenite (colorless)
- Helliodor (yellow)
- Morganite (pink, orange)



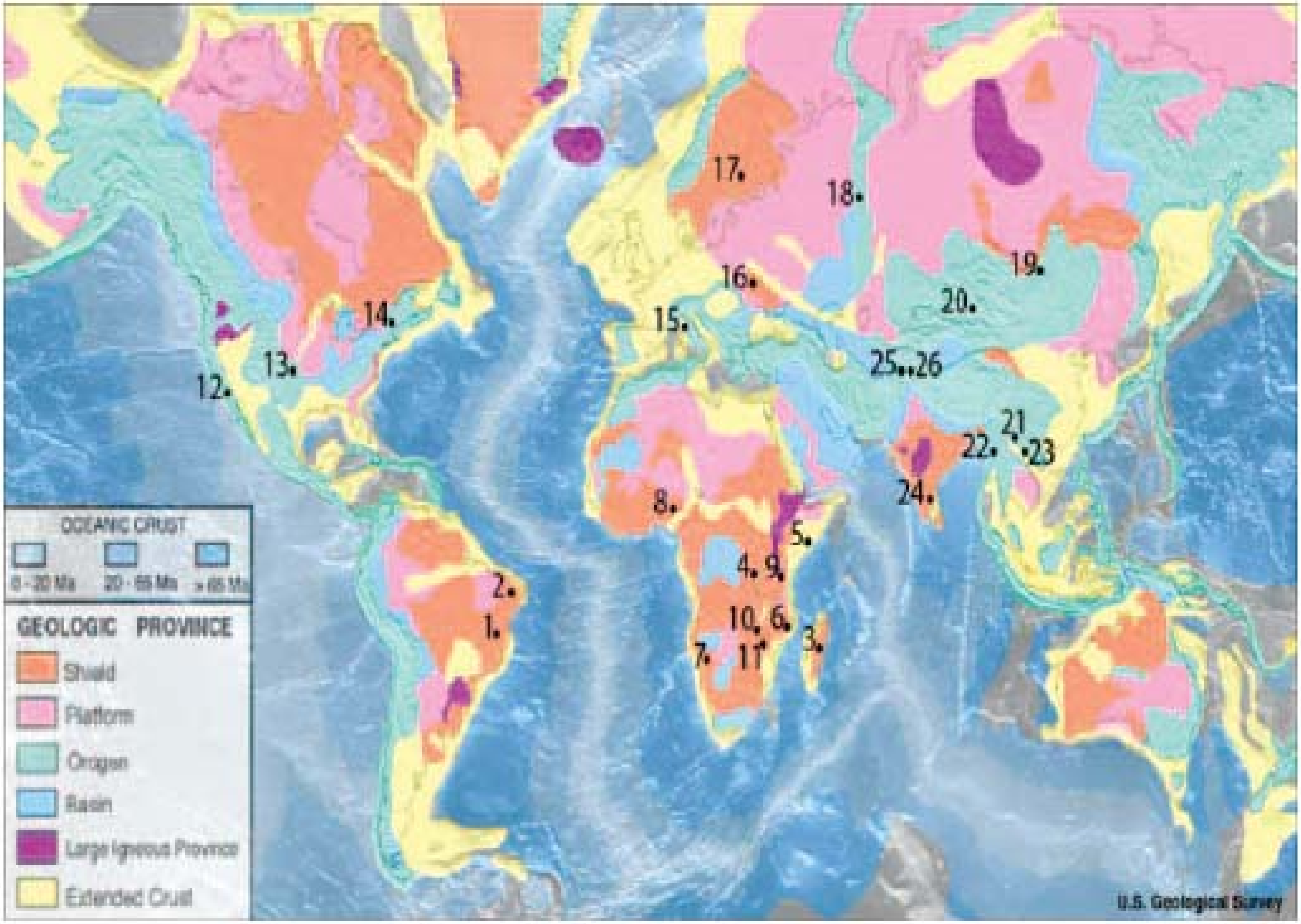



**FIGURE 6** Major gem-pegmatite districts of the world; the numbers correspond to the districts in TABLE 2. Geologic Province Map of the World, U. S. Geological Survey (http://earthquake.usgs.gov/research/structure/crust/maps.php)

Simmons et al., 2012

Table 2. Comparison of some beryllium minerals

| Mineral | Chemical Composition | % BeO |
|---|---|---|
| Barylite | $BaBe_2Si_2O_7$ | 15.4–15.8 |
| Bertrandite | $Be_4Si_2O_7(OH)_2$ | 39.6–42.6 |
| Beryl | $Be_3Al_2(SiO_3)_6$ | 10.0–14.0 |
| Beryllonite | $NaBePO_4$ | 19.8 |
| Chrysoberyl | $BeAlO_4$ | 16.9–19.7 |
| Danalite | $Fe_4Be_3(SiO_4)_3S$ | 12.7–13.8 |
| Eudidymite | $HNaBeSi_3O_8$ | 10.6–11.1 |
| Helvite | $Mn_4Be_3(SiO_4)_3S$ | 10.5–15.0 |
| Herderite | $CaBePO_4(OH,F)$ | 15.0–15.8 |
| Phenakite | $Be_2SiO_4$ | 44.0–45.6 |

Adapted from Warner et al. 1959.

| Name, Formula | Colour | Hardness | Specific gravity | Lustre | Crystal form | Transparency | Fracture |
|---|---|---|---|---|---|---|---|
| Barylite $BaBe_2Si_2O_7$ | colourless, white, yellow | 7 | 4 | silky, greasy or vitreous | orthorhombic or monoclinic | transparent-translucent | brittle |
| Bertrandite $Be_4Si_2O_7(OH)_2$ | colourless, white, pale yellow | 6-7 | 2.6 | vitreous to pearly | orthorhombic | transparent | brittle |
| Beryl $Be_3Al_2Si_6O_{18}$ | white, pale-blue, green | 7.5-8 | 2.6-2.9 | vitreous | trigonal | transparent-translucent | uneven to conchoidal, brittle |
| Chrysoberyl $BeAl_2O_4$ | green, yellow, red | 8.5 | 3.5-3.8 | vitreous | orthorhombic | transparent-translucent | conchoidal to uneven, brittle |
| Eudidymite $NaBeSi_3O_7(OH)$ | colourless, white, yellow, blue | 6-7 | 2.55 | vitreous | monoclinic | transparent-translucent | brittle |
| Helvite $(Mn,Fe,Zn)_4Be_3Si_3O_{12}S$ | brown, yellow, grey | 5.5-6.5 | 3.2-3.4 | vitreous to resinous | cubic | transparent-translucent | conchoidal to uneven, brittle |
| Phenakite/ Phenacite $Be_2SiO_4$ | colourless, white | 7.5-8 | 2.9-3.0 | vitreous | trigonal | transparent | conchoidal, brittle |

Table 1: Properties of some beryllium minerals.

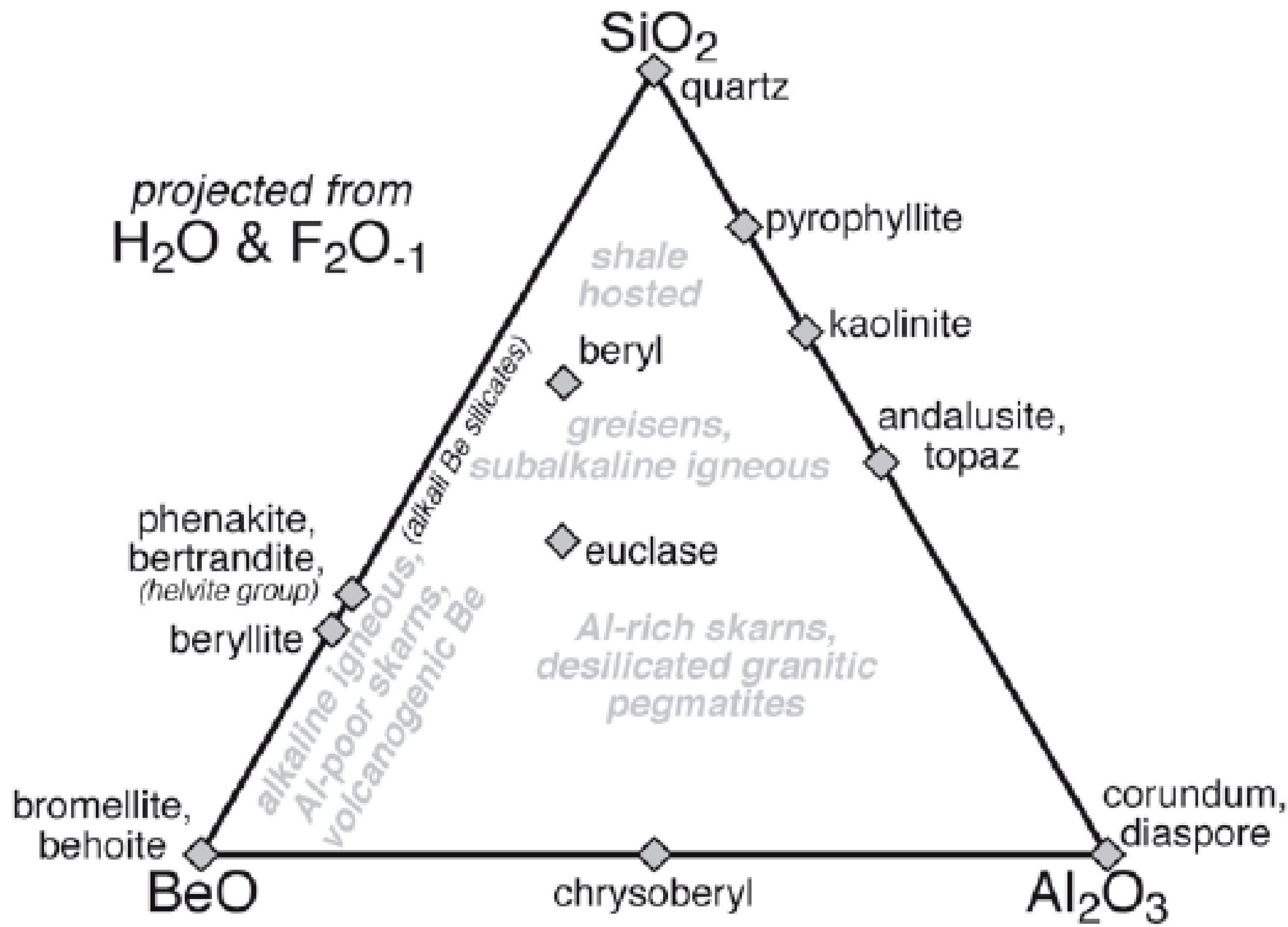



**Figure 1.** Chemography of the principal solid phases in the $BeO$-$Al_2O_3$-$SiO_2$-$H_2O$(-$F_2O_{-1}$) "BASH" system with the projected positions of helvite group and alkali Be silicates. Also shown are generalized fields for some of the major types natural of occurrences (cf. Table 1, Fig. 4; see text for discussion).

Barton and Young

# GEOLOGY

# TYPES OF BERYLLIUM DEPOSITS

TABLE 5. Types of beryllium deposits (Beus, 1966; Barton and Young, 2002; Sabey, 2006). USGS Classification after Cox and Singer (1986), Ludington and Plumlee (2009), and Foley et al. (2010).

| Type of Be deposit | USGS Classification | Example |
|---|---|---|
| Pegmatites | 13 | Tanco, Canada |
| Volcanogenic Be (volcanic-hosted replacement, volcanic-epithermal, Spor Mountain Be-F-U deposits) | Volcanogenic Be deposits | Spor Mountain, Utah |
| Carbonate-hosted replacement and skarn (Mo-W-Be, F-Be, Fe-Mn) | 14a | Ermakovskoe, Russia |
| Alkaline igneous rocks (disseminations and veins in peralkaline rocks and fenites) | 11 | Strange Lake, Canada |
| Granite/rhyolites (topaz rhyolites) | 25h | Taylor Creek, NM |
| Tin skarns | 15c, 14b, 14c | Lost River, Ak |
| Greisens | Mo-W greisens, 15c | Boomer, Colorado |
| Veins | – | Columbia black shale |
| Porphyry molybdenum (±copper, tungsten) | 16, 21a, 21b | Questa, NM |
| Metamorphic (schist) | 31c | Regal Ridge, Yukon, Canada |
| Placer (mostly beryl and babefphite) | – | – |
| Coal | – | – |

Table 3. Significant beryllium deposits and resources

| Deposit(s) | Location | Resource, *tons BeO* | Grade, % *BeO* | Source |
|---|---|---|---|---|
| **Volcanic rock-hosted** | | | | |
| Spor Mountain | Utah, United States | 72,315* | 0.71 | This volume |
| **Pegmatite** | | | | |
| Various | North Carolina, United States | 122,800 | 0.05 | Griffitts 1954 |
| Various | Brazil | 42,000 | 0.04 | Soja and Sabin 1986 |
| Various, Black Hills | South Dakota, United States | 13,300 | na† | Runke, Mullen, and Cunningham 1952 |
| Tanco | Canada | 1,800 | 0.20 | Cerný 1982 |
| Hellroaring Creek | Canada | <1,000 | 0.10 | Barton and Young 2002 |
| **Replacement and skarn** | | | | |
| McCullough Butte | Nevada, United States | 47,000 | 0.027 | Barton and Young 2002 |
| Sierra Blanca | Texas, United States | 11,300 | >2.0 | Anon. 1986 |
| Ermakovskoe | Russia | >10,000 | 1.3 | Barton and Young 2002 |
| Lost River | Alaska, United States | >10,000 | 0.3–1.75 | Sainsbury 1963 |
| Iron Mountain | New Mexico, United States | <1,000 | 0.2–0.7 | Jahns 1944 |
| **Peralkaline rock-hosted** | | | | |
| Strange Lake | Canada | 42,000 | 0.08 | Richardson and Birkett 1996 |
| Ilimaussaq | Greenland | >20,000 | na | Barton and Young 2002 |
| Thor Lake | Canada | 13,300 | 0.76 | Richardson and Birkett 1996 |
| Seal Lake | Canada | 6,800 | 0.35–0.40 | Richardson and Birkett 1996 |
| **Greisen** | | | | |
| Aqshatau | Kazakhstan | 16,000 | 0.03–0.07 | Barton and Young 2002 |
| Boomer | Colorado, United States | <1,000 | 2.0–11.2 | Hawley 1969 |
| **Vein** | | | | |
| Gold Hill | Utah, United States | >5,000 | 0.5 | Shawe 1966 |
| Mount Wheeler | Nevada, United States | <1,000 | 0.75 | Shawe 1966 |

* Remaining reserves 2004.
† na = not available.

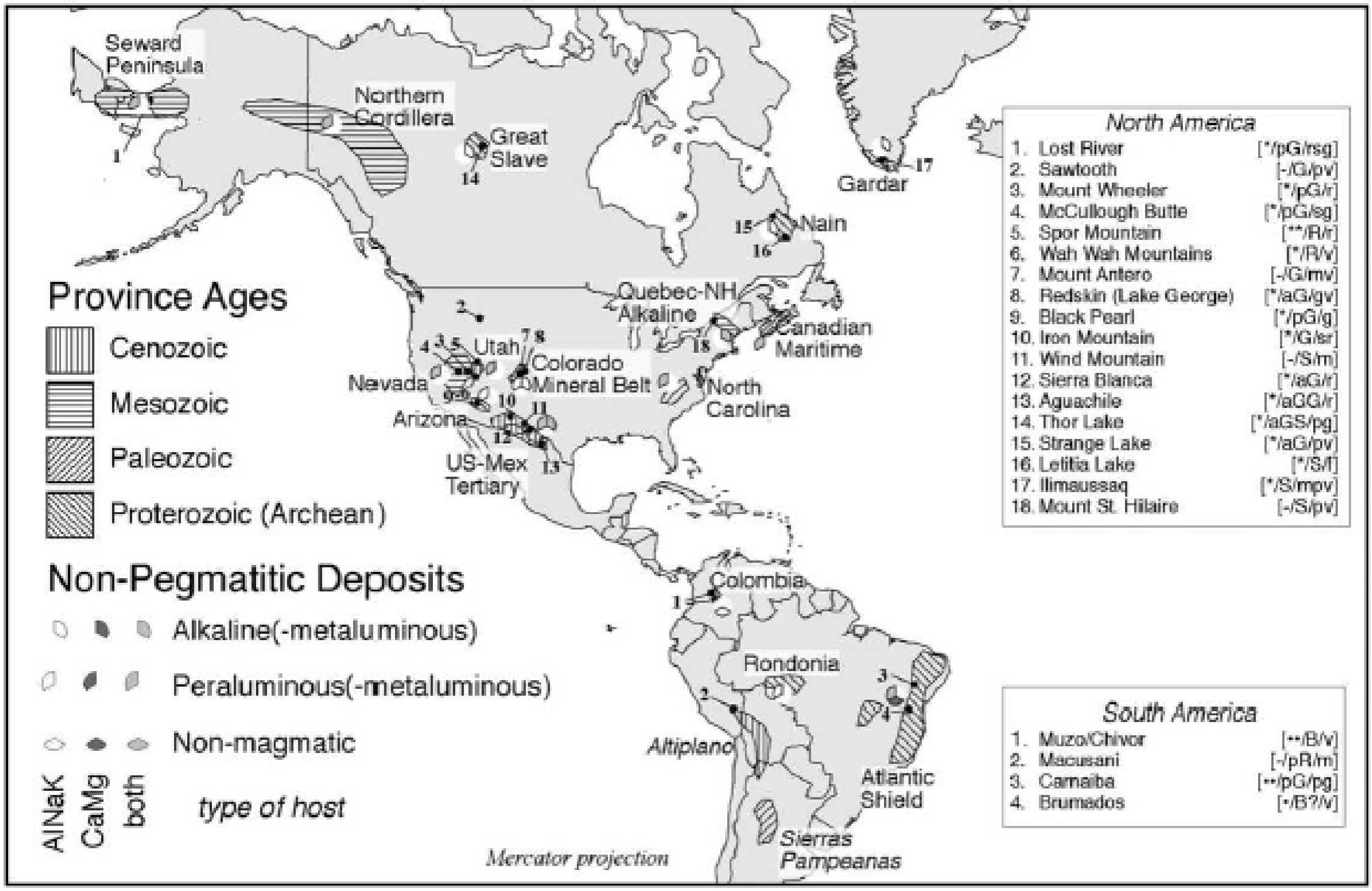
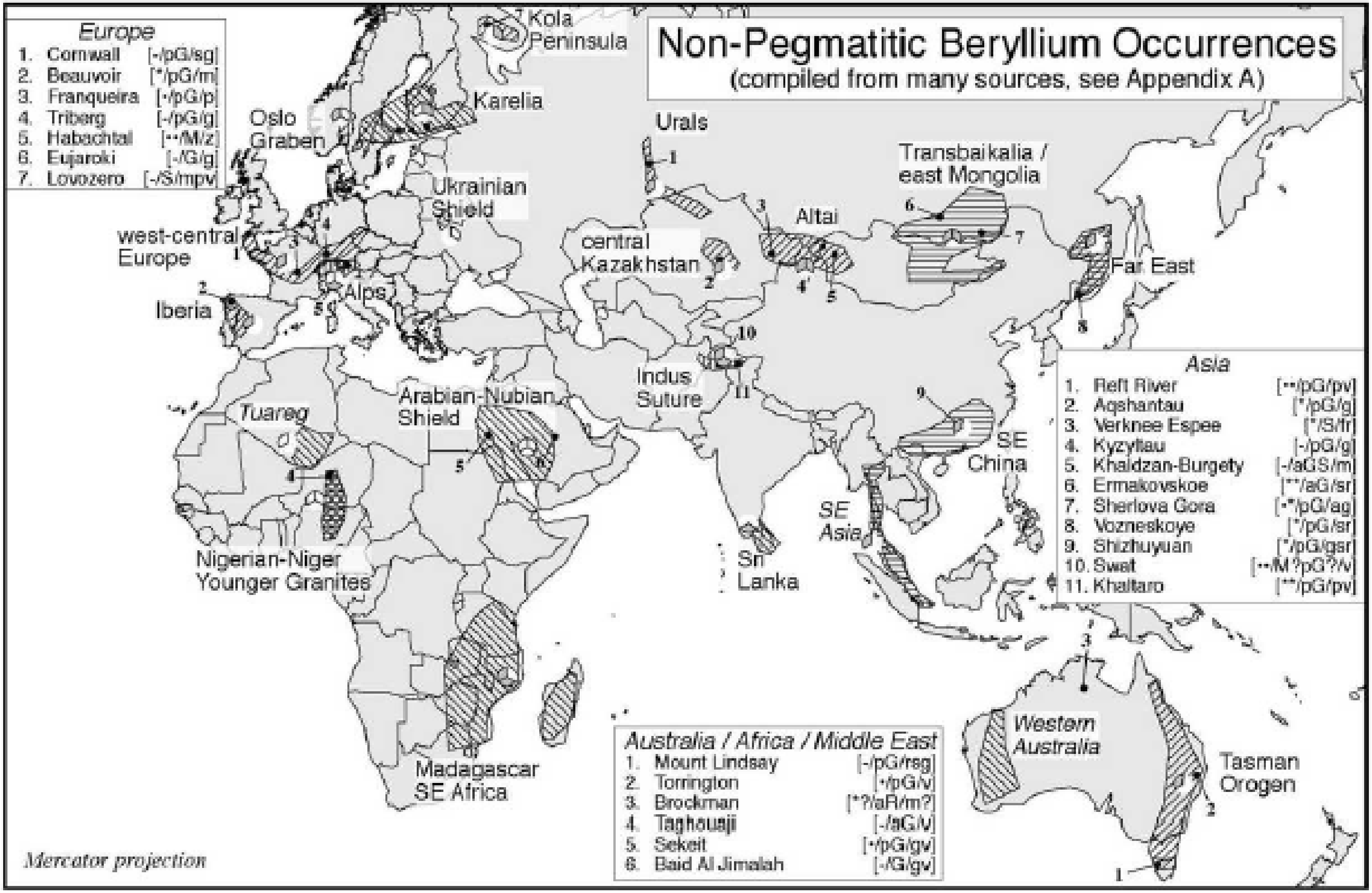


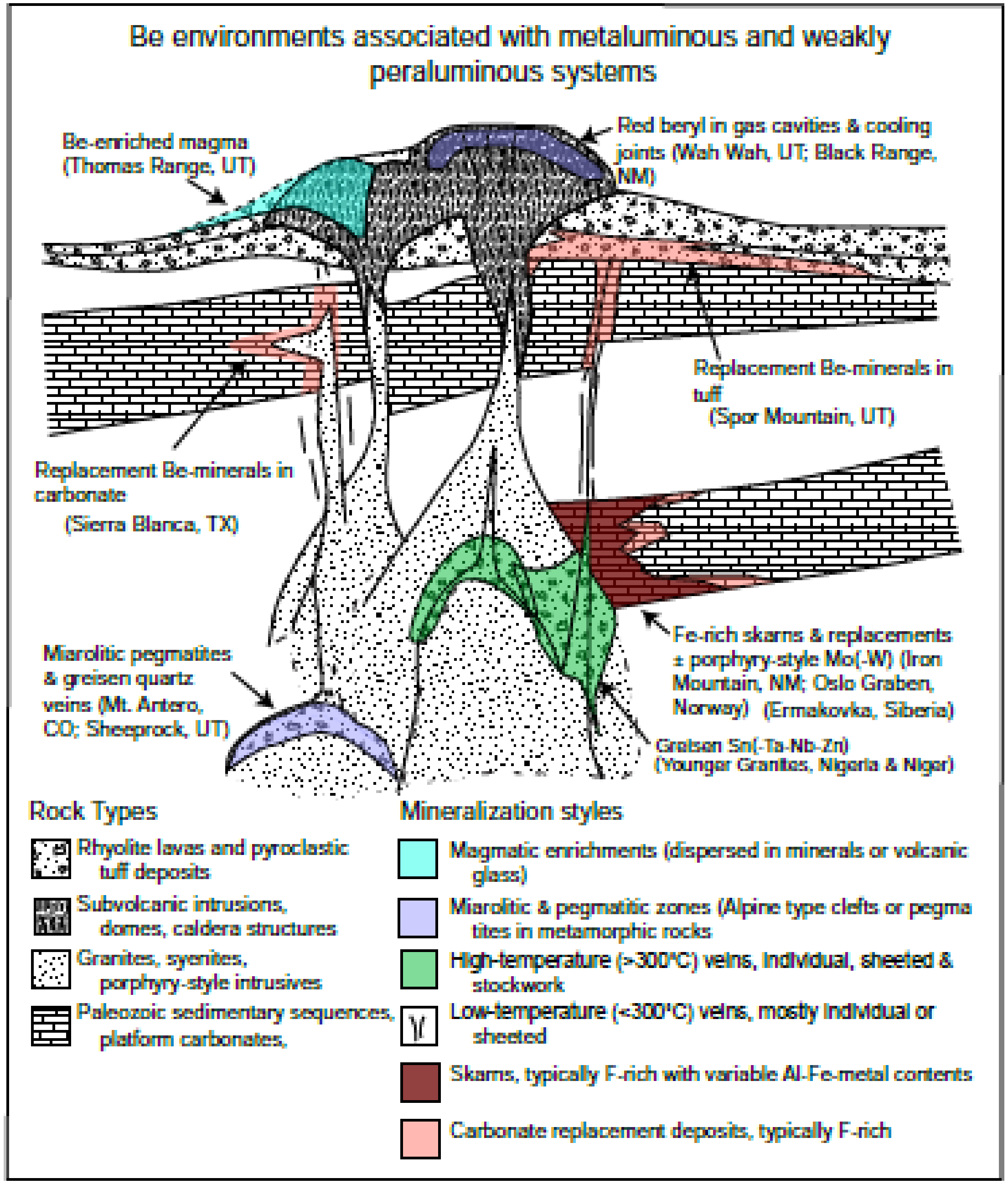

**Figure 2.** Map showing the location of non-pegmatitic Be occurrences and the Be-bearing belts that are mentioned in this paper. Deposit-type assignments can be uncertain or generalized depending on available information and the complexity of the region. The Symbolism for the key deposits is: significance (0-2 stars) / petrologic association **(figure and caption continued next page >>)**

Barton and Young


Lost River, Alaska
Seward Peninsula
Tanco pegmatite, Manitoba
Spor Mountain, Utah
Honey Comb Hills, Utah
Wah Wah Mountains, Utah
North Carolina pegmatites
Apache Warm Springs, New Mexico
Sierra Blanca, Texas
Aguachile, Mexico
Mascusani, Peru
Minas Gerais, Brazil
MERCATOR PROJECTION




Barton and Young




A generalized cross-section showing geologic setting for the major types of Be deposits associated with metaluminous and weakly peraluminous magma systems and the relationship of volcanogenic Be deposits such as Spor Mountain to other type of Be deposits that are associated with magmas of this general composition. Modified from Barton and Young (2002).

# Volcanic-hosted replacement deposits

**Table 1.** Deposits and occurrences considered in developing the volcanogenic epithermal beryllium (Be) deposit model.

[Data summarized primarily from Barton and Young (2002, their appendix A); Mt, million metric tons; kT, kiloton; Ma, million years ago; ppm, parts per million]

| Deposit/ occurrence | Age of complex/ volcanic unit/ mineralization | Brief description of occurrence and contained Be ore | Primary data references |
|---|---|---|---|
| Spor Mountain/ Utah, U.S.A. | Middle Cenozoic/ ≈21 Ma/≈21 Ma and younger | Bertrandite in fluorite-silica replacement of carbonate clasts in lithic tuff (7 Mt at 0.72% BeO), extensive Li-Zn-bearing K-feldspar and clay alteration; overlying 6–7 Ma topaz rhyolites have red beryl | Griffitts, 1964; Shawe, 1966, 1968; Lindsey and others, 1973; Lindsey, 1977; Ludwig and others, 1980; Burt and Sheridan, 1981; Baker and others, 1998 |
| Honey Comb Hills/ Utah, U.S.A. | Middle Cenozoic | Be in fluorite-silica replacements, stringers, veinlets in tuff | Montoya and others, 1964; McAnulty and Levinson, 1962 |
| Wah Wah Mountains/Utah, U.S.A. | Middle Cenozoic/ ≈23 Ma | Topaz rhyolite with late red beryl + kaolinite in fractures with early Mn-Fe oxides; main gem red beryl source | Keith and others, 1994; Thompson and others, 1996 |
| Apache Warm Springs/Socorro County, New Mexico, U.S.A. | Middle Cenozoic/ ≈28 Ma/≈<28–>24.4 Ma, bracketed by stratigraphy | Bertrandite in small quartz veins and stringers in fractures and disseminations in rhyolite and rhyolite ash-flow tuff, intense acid-sulfate alteration | McLemore, 2010a,b and references therein; Shawe, 1966; Hillard, 1969; Be Resources, Inc. at *http://www.beresources.com;* accessed December 10, 2011 |
| Aguachile/ Coahuila, Mexico | Middle Cenozoic/ ≈28 Ma | Bertrandite-adularia-bearing fluorite replacement (17 Mt at 0.1% BeO) adjacent to alkaline rhyolite and riebeckite quartz syenite | Levinson, 1962; McAnulty and others, 1963; Griffitts and Cooley, 1978; Simpkins, 1983 |

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| | | | |
|---|---|---|---|
| Sierra Blanca/ Texas, U.S.A. | Middle Cenozoic/ 36.2 Ma/coeval with intrusion | Fluorite-rich replacement bodies in limestone adjacent to Li-Be-Zn-Rb-Y-Nb-REE-Th-rich alkaline cryolite-bearing rhyolites; 850 kT at 1.5% BeO as bertrandite, phenakite (behoite, berborite, chrysoberyl); minor grossularitic skarn; clays + analcime | McAnulty and others,1963; Price and others, 1990; Rubin and others, 1987, 1988, 1990; Henry, 1992 |
| Northern Basin and Range Province/ Oregon, Idaho, Nevada, Utah, and California, U.S.A. | Middle Cenozoic/ Miocene | Mainly western Utah Be belt; most occurrences in volcanic rocks, but also skarn (helvite-beryl) and granite-hosted occurrences—dominant Be producer; magmas up to 80 ppm Be | Warner and others, 1959; Shawe, 1966; Lindsey, 1977; Burt and Sheridan, 1986; Congdon and Nash, 1991 |
| Andean Altiplano/ Macusani, Peru | Middle Cenozoic/ Miocene (4.2 Ma; 9.3 Ma) | Beryllium minerals apparently rare, but wide-spread. Miocene rare-metal-enriched felsic intrusive and volcanic centers, many with Sn-Ag-(±B) ores, fluorite is relatively uncommon; Macusani tuff | Pichavant and others, 1988a,b; Lehmann and others, 1990; Dietrich and others, 2000; Noble and others, 1984 |
| Transbaikal/ eastern Mongolia Teg-Ula | Mesozoic | Many deposit types associated with mainly Mesozoic granitoids ranging from peraluminous to peralkaline; volcanic-hosted Be in Mongolia | Kovalenko and Yarmolyuk 1995; Kremenetsky and others, 2000; Reyf and Ishkov, 2006; Lykhin and others, 2010 |
| Shixi/ Zhejiang, South China | Mesozoic? | Hypabyssal dikes of porphyritic sodic rhyolite, albitized and sercitized, high Be (as helvite, beryl, bertrandite, and euclase) and Nb, Ta, Zr, F | Lin, 1985 |
| Brockman/Western Australia | Paleoproterozoic/ 1870 Ma | Hydrothermally altered fluorite-bearing alkali rhyolite with Nb-Zr-REE-Ta-Be enrichment (4.3 Mt at 0.08% BeO); predates orogenesis | Ramsden and others, 1993; Taylor and others, 1995a,b |

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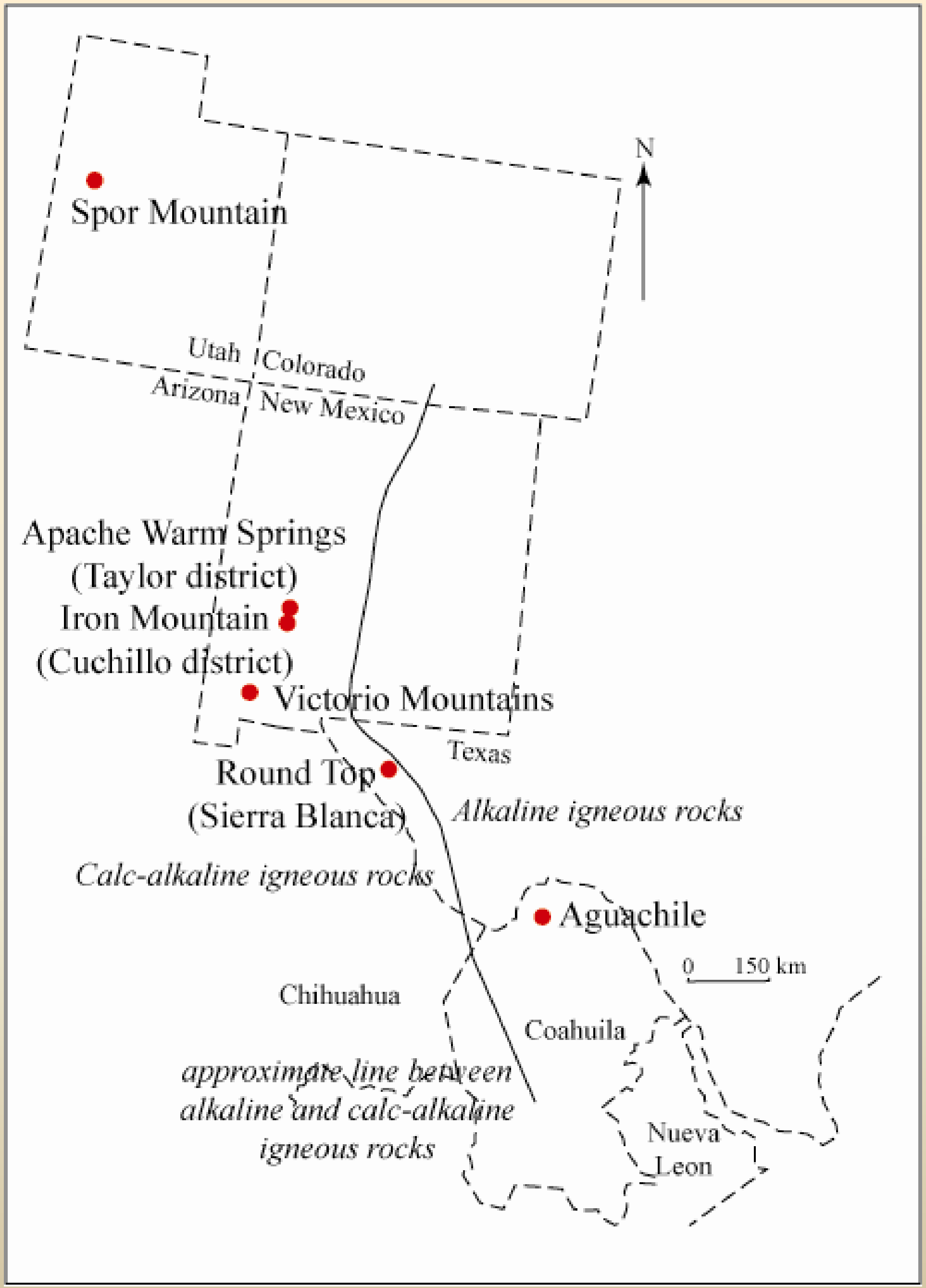


Location of selected beryllium deposits found in southwestern U.S. and Mexico. Approximate line separating the Tertiary alkaline and calc-alkaline igneous rocks is from Price et al. (1987) and McLemore (1996).

# SPOR MOUNTAIN, UTAH

# BRUSH WELLMAN BERYLLIUM PLANT

[show on map]


This large industrial plant in the remote Sevier Desert of western Utah is one of the only sources of concentrated beryllium in the world. The plant is a mill and finishing facility for beryllium, a high-strength, lightweight metal used in military, aerospace, and medical industries. The ore for the plant comes from Brush Wellman's mine, located in the Topaz-Spor Mountains, 50 miles west, which is North America's only developed source for the metal. The facility is located here due to the remoteness of the area, as beryllium dust is highly toxic, and the proximity of a large source of power: the Intermountain Power Project, a massive coal-fired power plant located a few miles away.

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| | |
|---|---|
| **Visitation:** | Located next to the road, at the intersection of Highway 6 and 174, 10 miles north of Delta. |
| **Coordinates:** | 39.467606, -112.436913 |
| **General Location:** | Ten miles N of Delta |
| **State:** | Utah |

TABLE 3. Production and reserves from the Spor Mountain mine owned by Brush Wellman (metric tons Be content, McNeil, 2004; Brush Engineered Materials, Inc., 2004, 2008, 2009).

| Year | Bertrandite processed tons | Grade % Be | Proven bertrandite reserves | Grade % Be | Probable bertrandite reserves | Grade % Be |
|---|---|---|---|---|---|---|
| Total 1969-2009 | 3,000,000 | ~0.2 | – | – | – | – |
| 2009 | 39,000 | 0.330 | 6,425,000 | 0.266 | 3,519,000 | 0.232 |
| 2008 | 64,000 | 0.321 | 6,454,000 | 0.266 | 3,519,000 | 0.232 |
| 2007 | 52,000 | 0.321 | 6,531,000 | 0.266 | 3,519,000 | 0.232 |
| 2006 | 48,000 | 0.352 | 6,550,000 | 0.267 | 3,519,000 | 0.232 |
| 2005 | 38,000 | 0.316 | 6,601,000 | 0.268 | 3,519,000 | 0.232 |
| 2004 | 39,000 | 0.248 | 6,640,000 | 0.268 | 3,519,000 | 0.232 |
| 2003 | 41,000 | 0.224 | 6,687,000 | 0.267 | 3,519,000 | 0.232 |
| 2002 | 40,000 | 0.217 | 6,730,000 | 0.267 | 3,519,000 | 0.232 |
| 2001 | 48,000 | 0.224 | 7,270,000 | 0.268 | 3,081,000 | 0.219 |
| 2000 | 84,000 | 0.235 | 7,690,000 | 0.263 | 3,166,000 | 0.217 |
| 1999 | 93,000 | 0.215 | – | – | – | – |

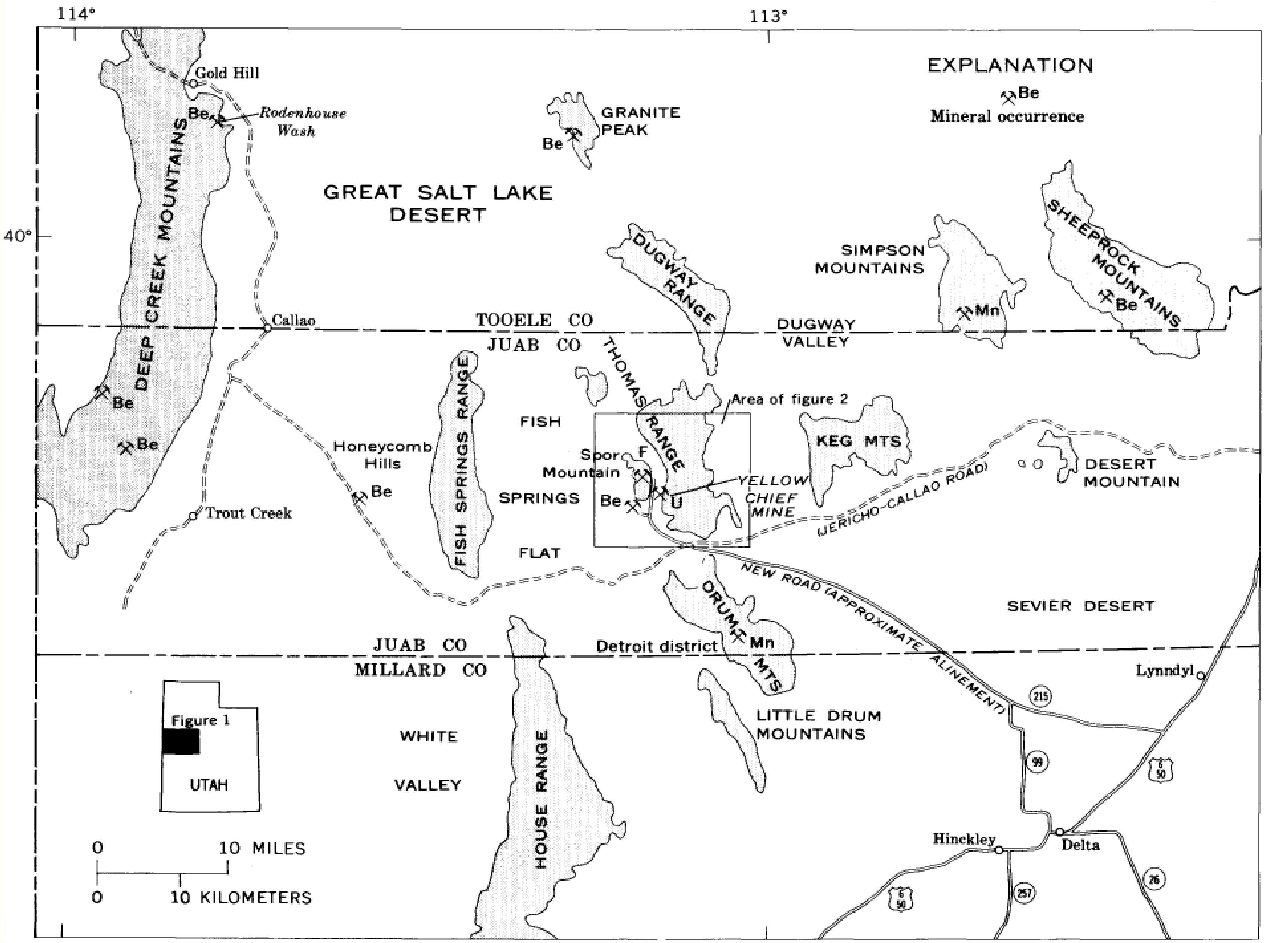
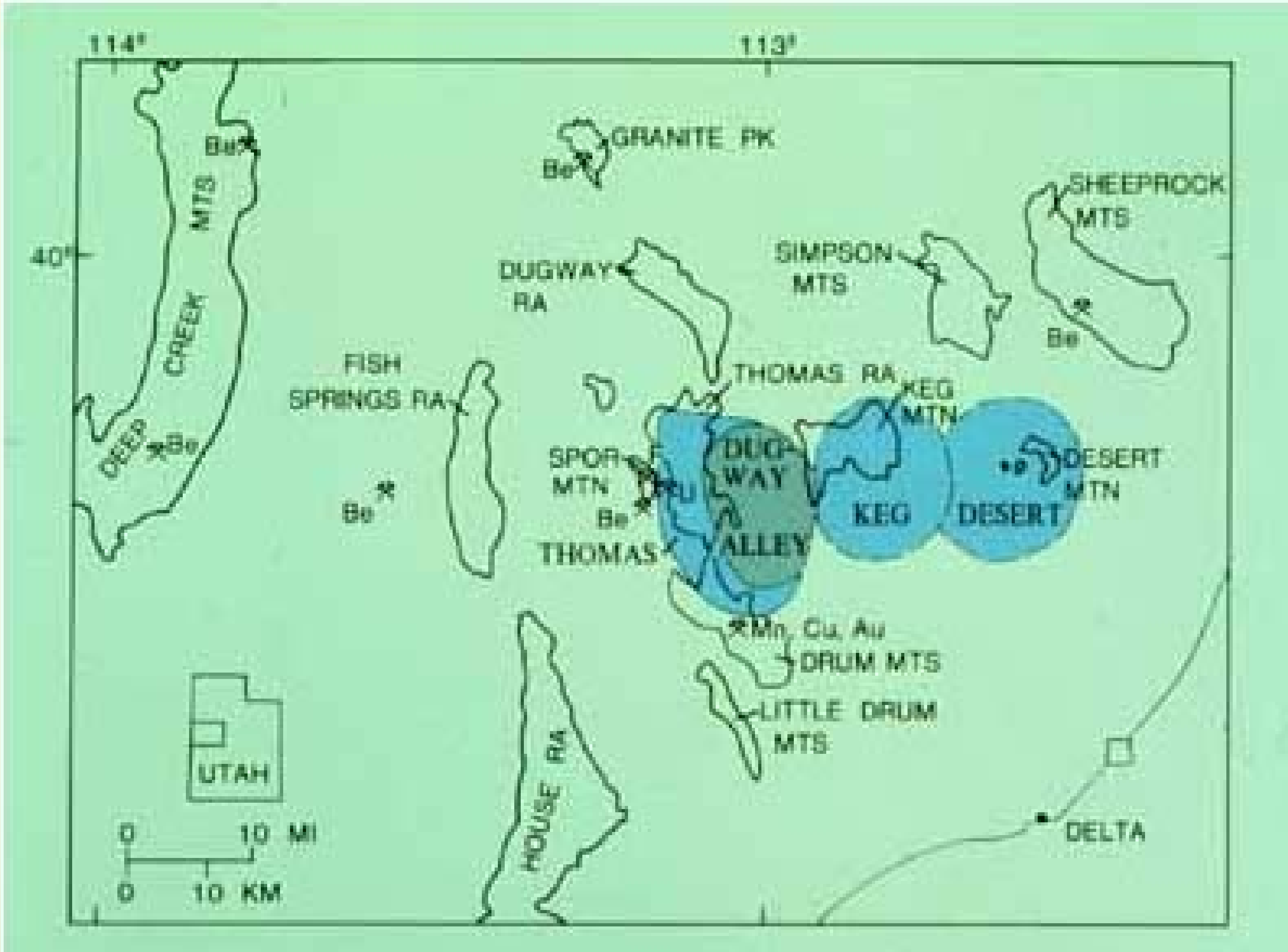
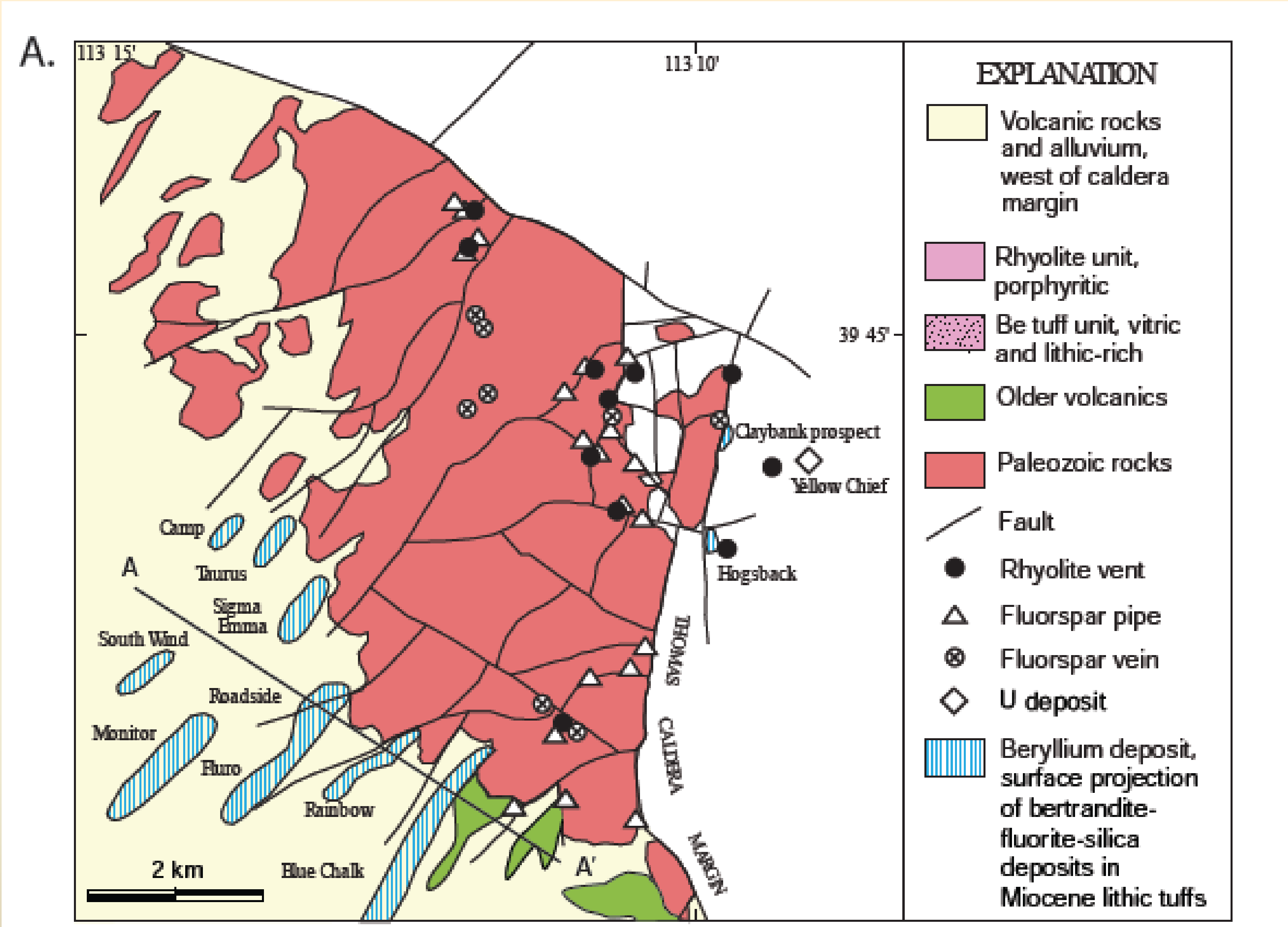



FIGURE 1. — Map showing location of Spor Mountain, other geographic features, and mineral occurrences mentioned in text.

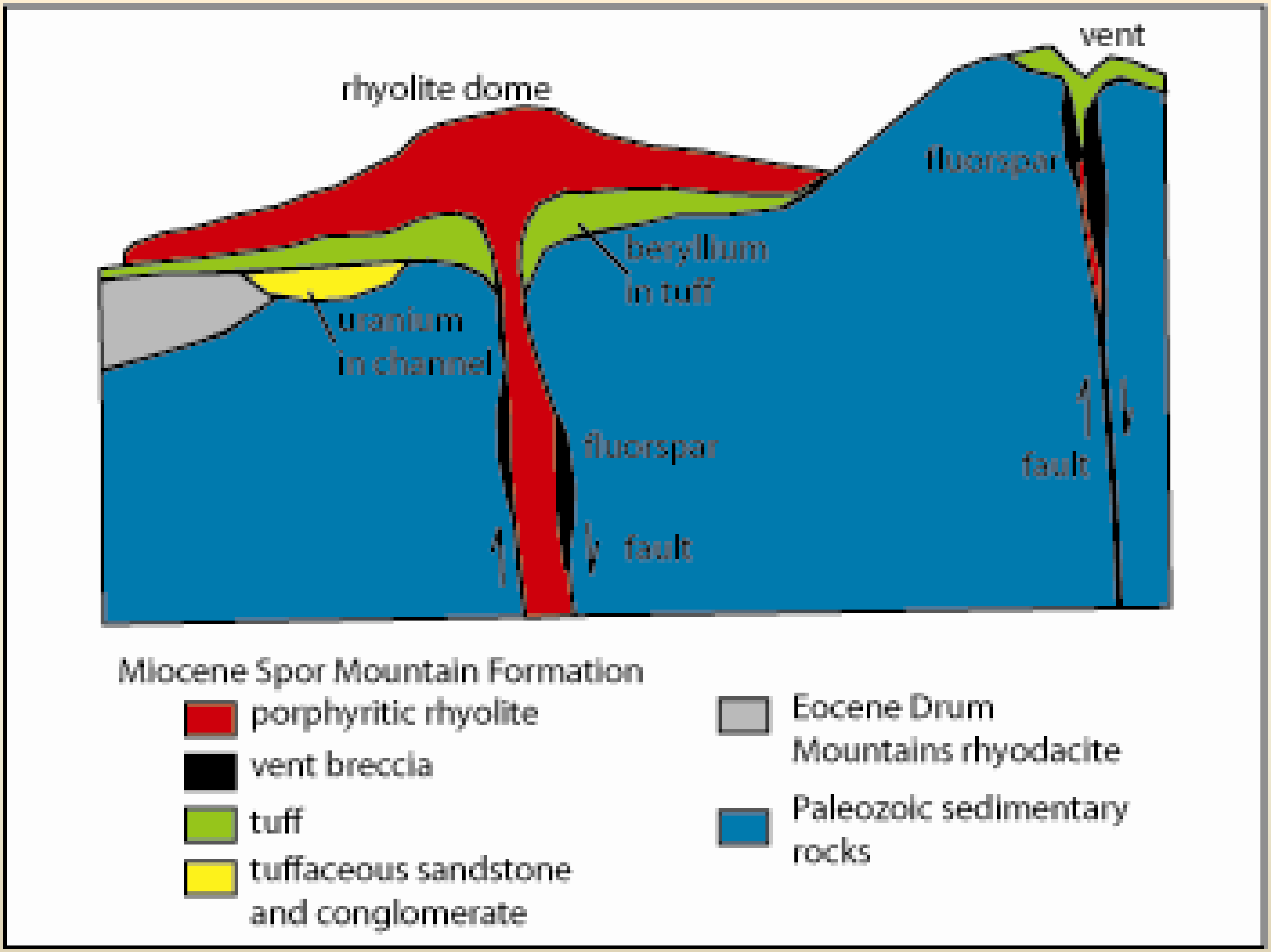
USGS PP 818-A




Beryllium belt of western Utah," also the "Deep Creek-Tintic belt. Be, F, U, Li, Cu, Au, base metals (USGS OF 98-524)

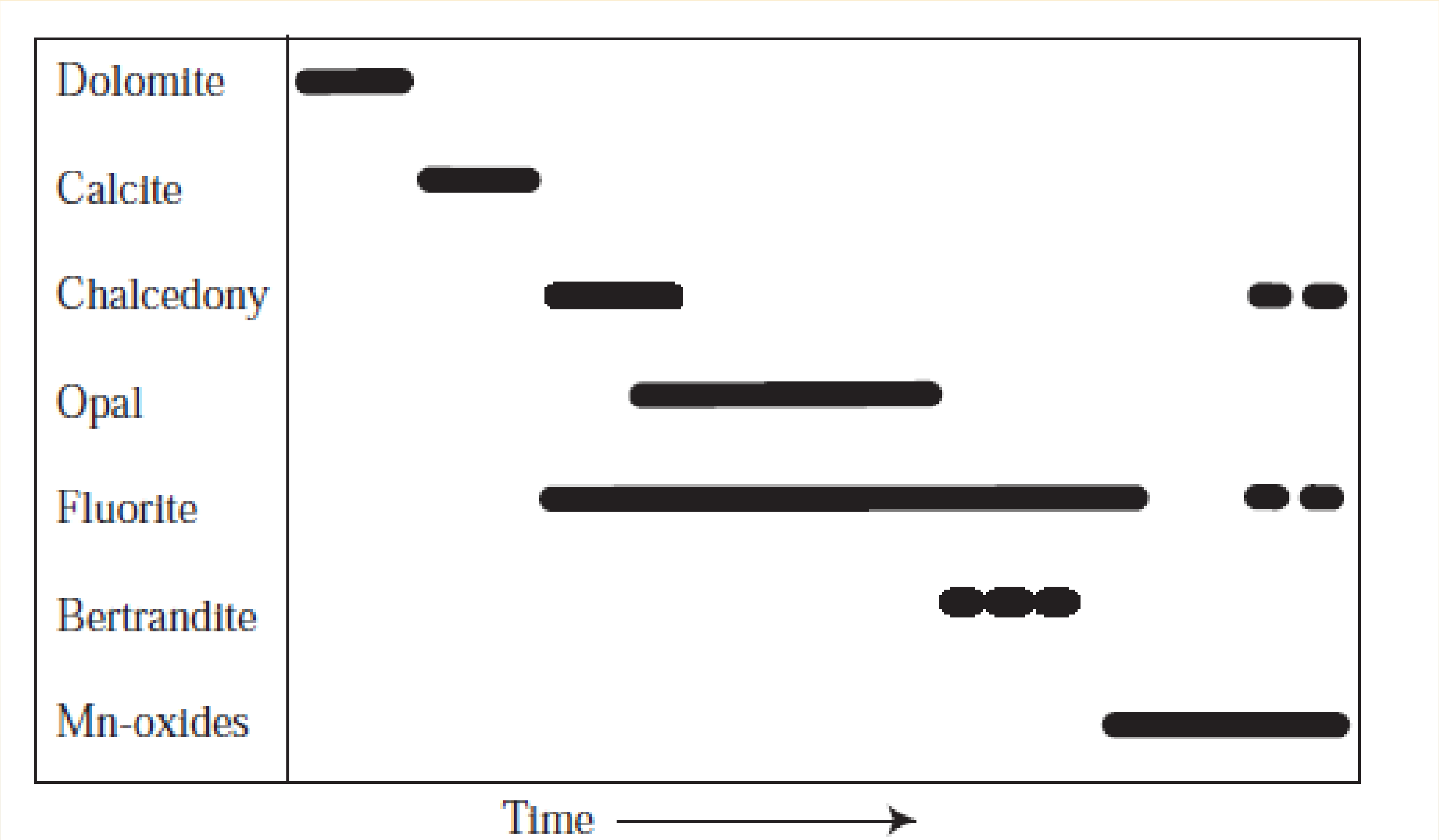


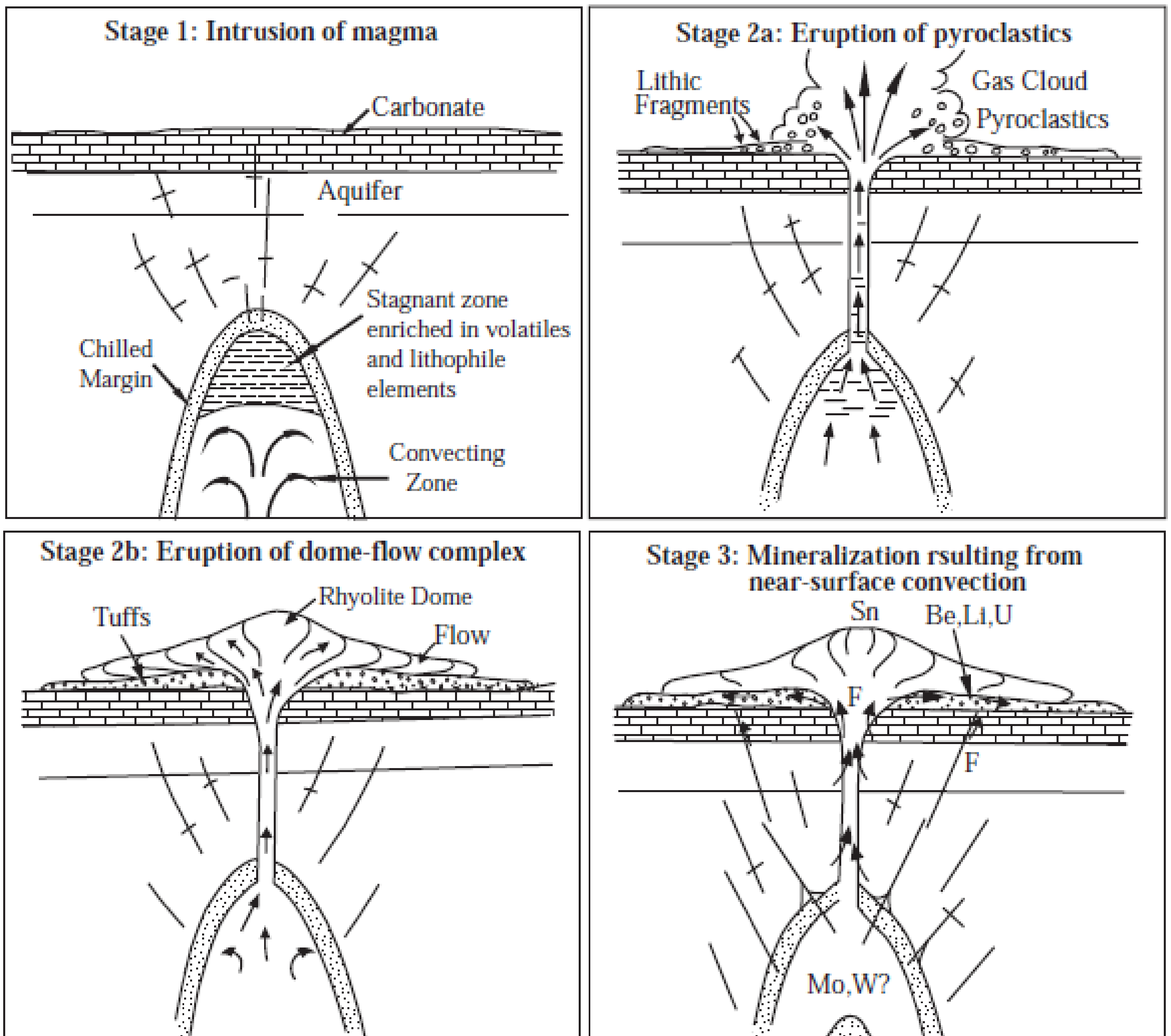

Generalized geologic map of the Spor Mountain and Thomas Range area, Utah, showing the locations and distribution of Be deposits and fluorite pipes. Modified from Lindsey, 2001.




# Spor Mountain—Cross section

# Paragenesis Spor Mountain






General model for formation of volcanogenic deposits of U and other lithophile elements, including Be, as proposed by Burt and Sheridan (1981).

| | | | |
|---|---|---|---|
| TIME (MY) | 42-39 | 38-32 | 21-6 |
| EVENT | CENTRAL VOLCANOES, CALDERA SUBSIDENCE | CALDERA FILLING, SUBSIDENCE | BASIN-RANGE FAULTING |
| MODE OF ERUPTION | FLOWS, ASH FLOWS | ASH FLOWS | FLOWS, DOMES, STRATIFIED TUFFS |
| ROCK TYPE | RHYODACITE-QZ LATITE | RHYOLITE | ALKALI RHYOLITE |
| MAJOR ELEMENTS | AL, FE, MG, CA, TI, MN | SI, K | SI, K, F |
| TRACE ELEMENTS | BA, CU, NI, SR, V | BA | BE, LI, NB, PB, SN, Y, YB, U, TH |
| TYPE OF MINERAL DEPOSITS | CU, AU, MN | ? | F, BE, U |

USGS OF 98-524

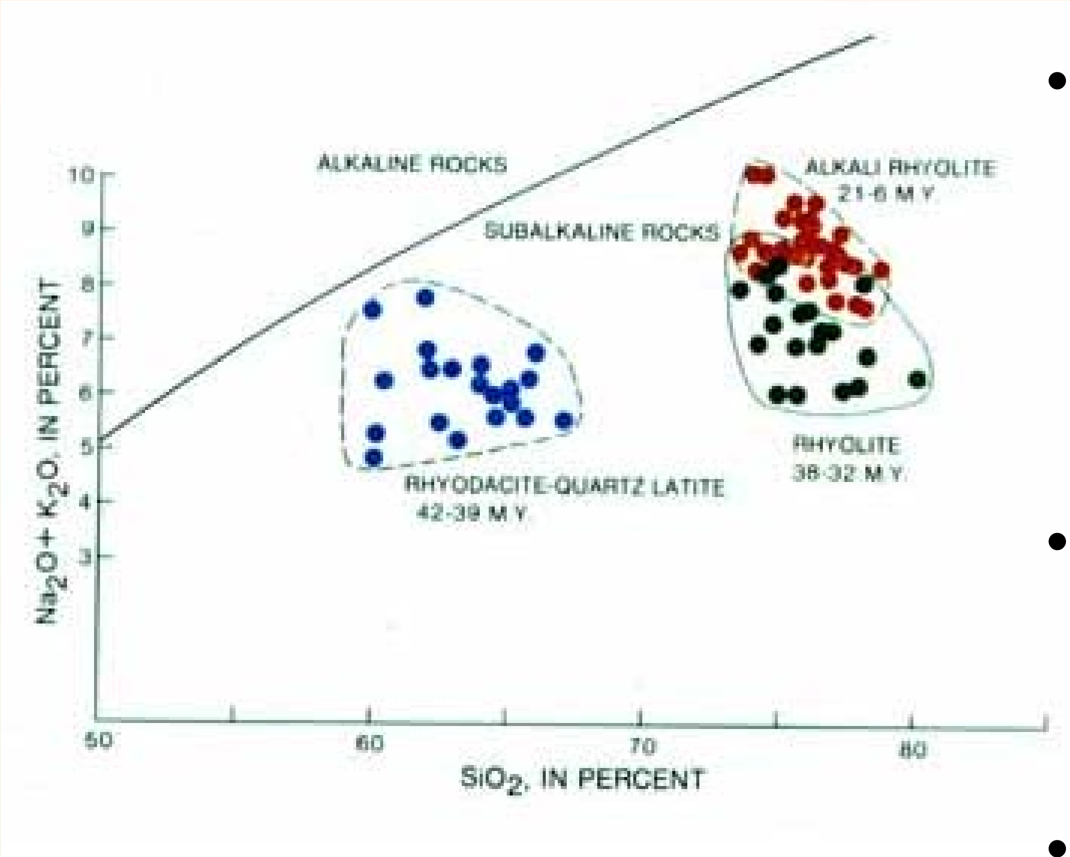
Be at Spor Mountain has been mined by Brush Wellman since about 1970, Roadslide pit in 1970 (USGS OF 98-524)

Monitor pit as it appeared in 1979, also Brush-Wellman (USGS OF 98-524)

# Controls of mineralization

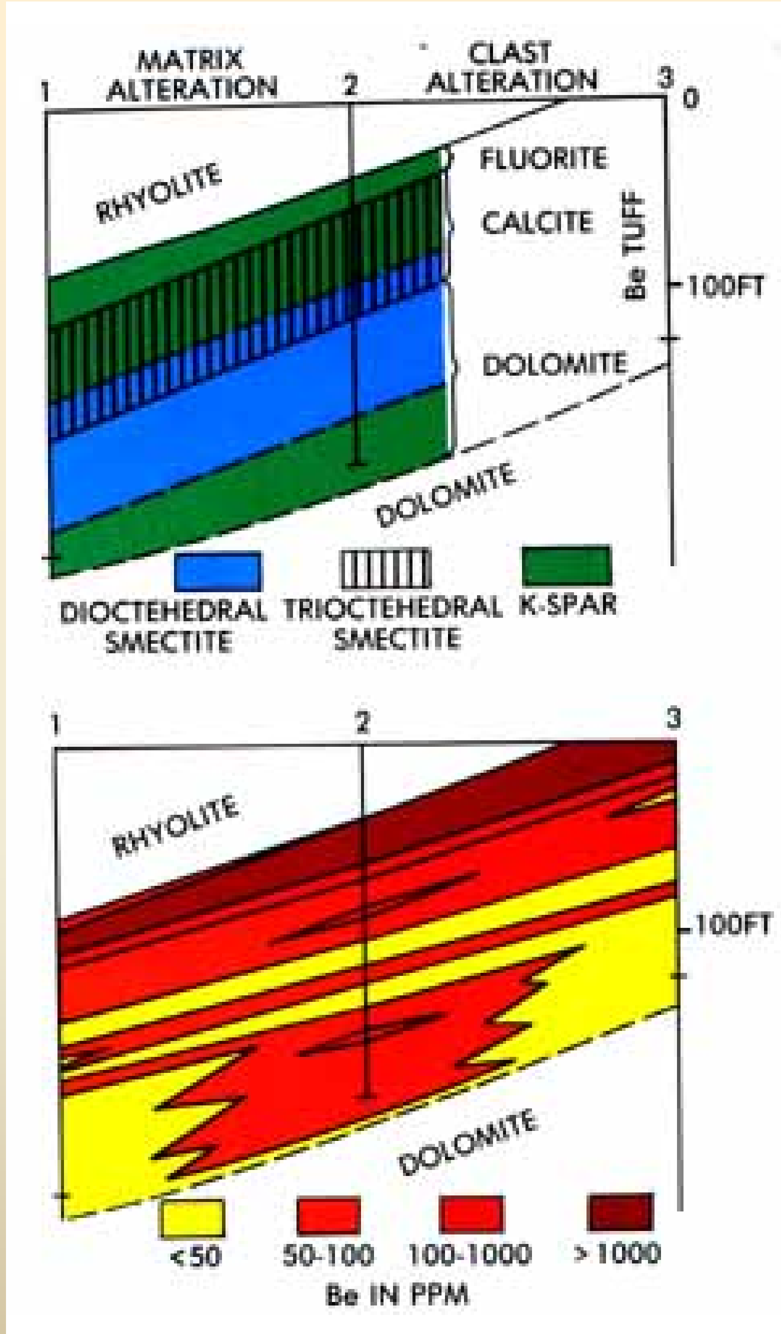
- magma chemistry
- favorable host rocks
- structure
- extension tectonics (F, U, Be, Li, alkaline rocks)


beryllium tuff (USGS OF 98-524)

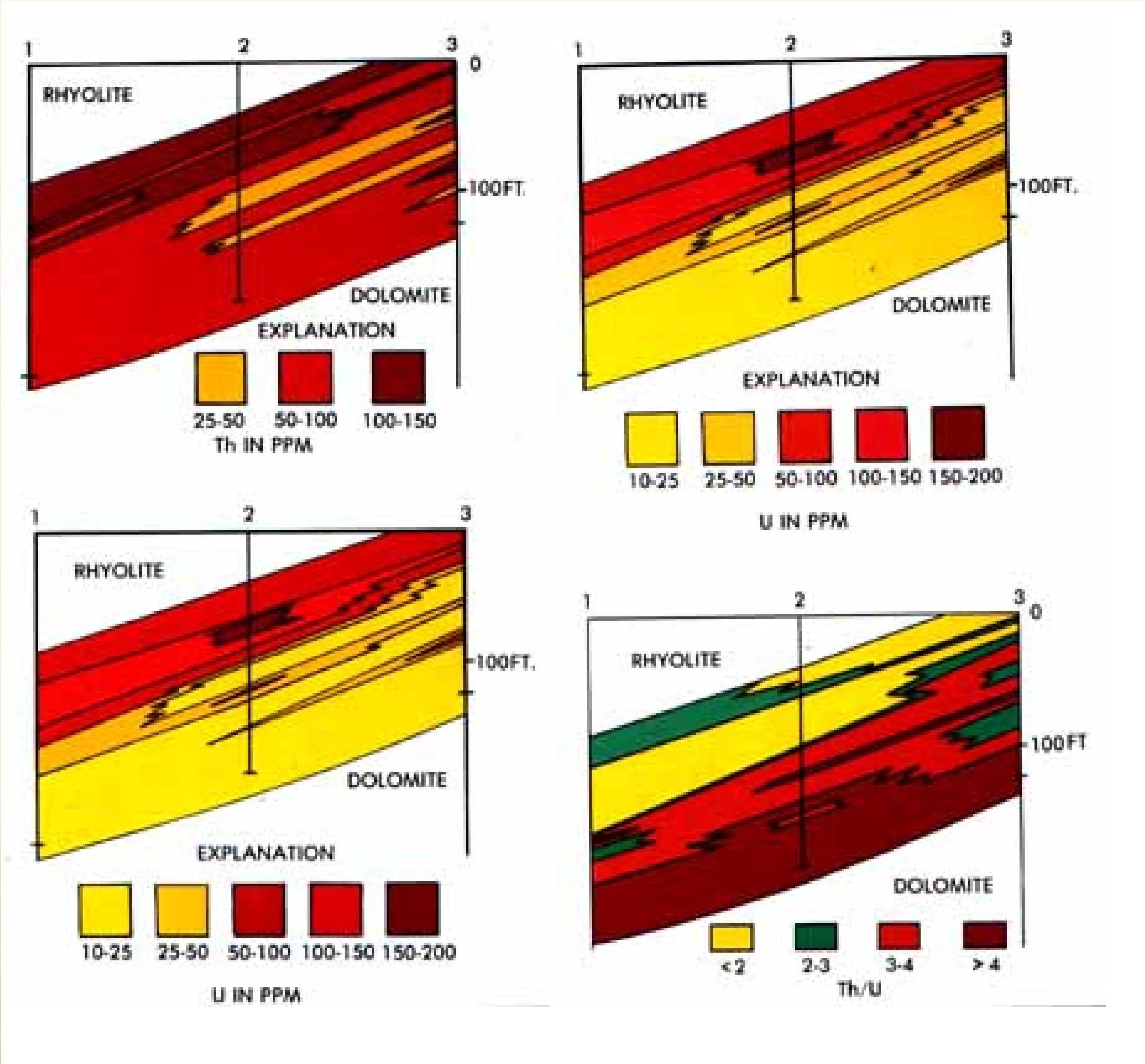



- First stage=rhyodacitic and quartz latitic composition, contain the largest trace concentrations of base metals such as Pb, Zn, and Cu
- Middle stage=mostly rhyolite, contain the smallest concentrations of all trace
- Third stage=Alkali rhyolite, post-caldera stage, contains the largest trace concentrations of lithophile elements such as Be, Li, thorium, and U

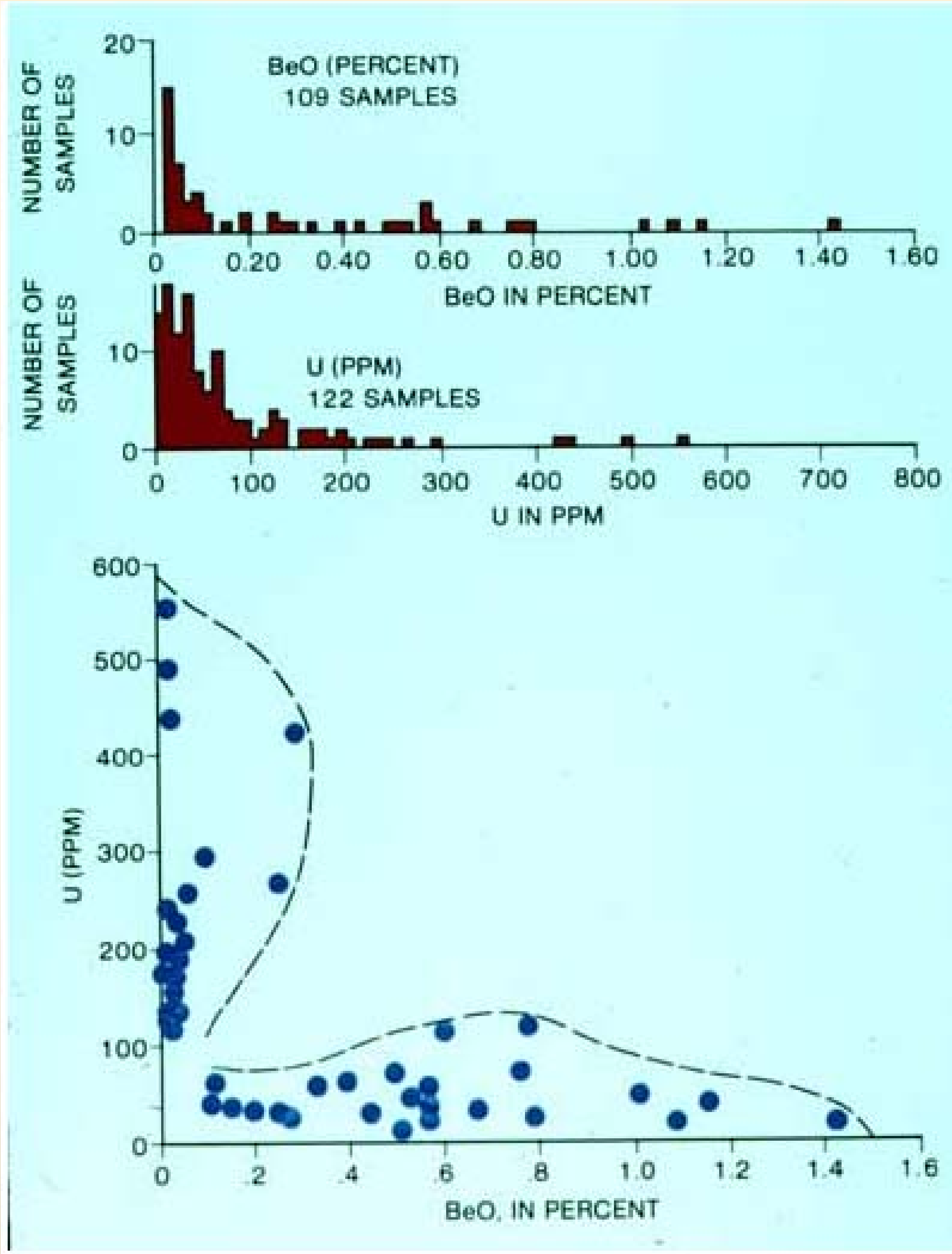
(USGS OF 98-524)




Be ore is concentrated in the upper part of the Be tuff member, as typified by the Roadside ore body (USGS OF 98-524)




Th follows Be, but U does not




Summarizes analyses of drill cuttings from many mineralized zones in the Be tuff member (USGS OF 98-524)

**Table 6.** A model hydrothermal fluid composition for Spor Mountain.

[Modified based on thermodynamic estimates and other data from Wood (1992)[1] and Murphy (1980)[2]. Mg/kg, milligrams per kilogram; ppb, parts per billion, ppm; parts per million; --, no unit]

| Parameter | Unit | Fluid characteristic |
|---|---|---|
| Temperature | °C | 200–100[1]; (160–140[2]) |
| pH | -- | 4–6 (no alunite, K-feldspar alteration); near-neutral[1] |
| $SiO_2$(aq) | -- | Activity fixed by cristobalite |
| Ca, Al, K | -- | Estimated by alteration assemblage of K-feldspar, Ca-clinoptilolite, beidellite-Ca (montmorillonite), rare sericite (muscovite) |
| $HCO_3$ | mg/kg | 100 |
| Cl | mg/kg | 1,000 |
| F | | >0.01 molal[1] or fixed by fluorite[1] |
| Mn | mg/kg | 1 |
| Be | mg/kg | 1[1]; (500 ppb–5 ppm) |
| Saturated phases | -- | Bertrandite, quartz, fluorite, pyrolusite |

# ROUND TOP MOUNTAIN, SIERRA BLANCA, TEXAS

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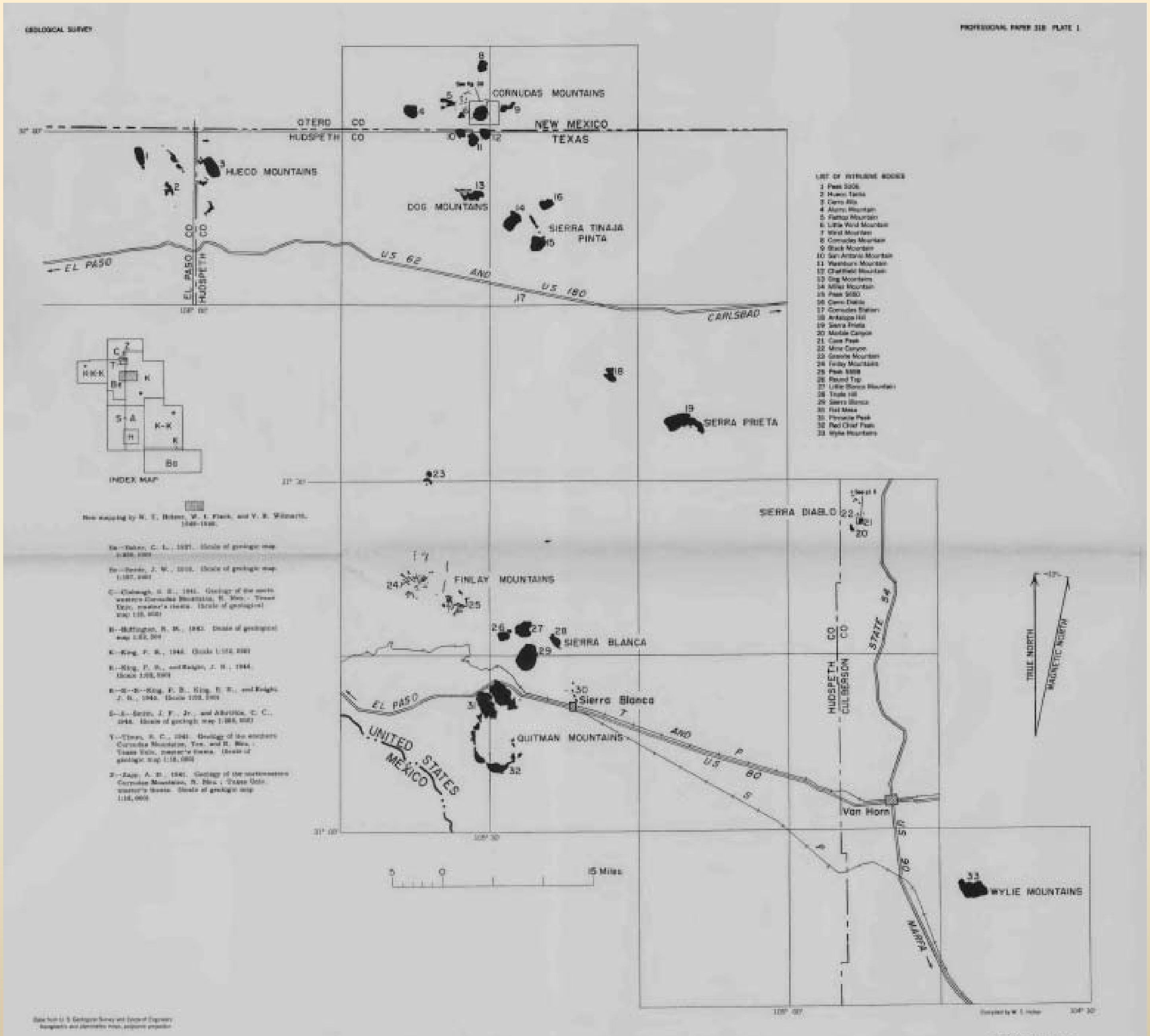
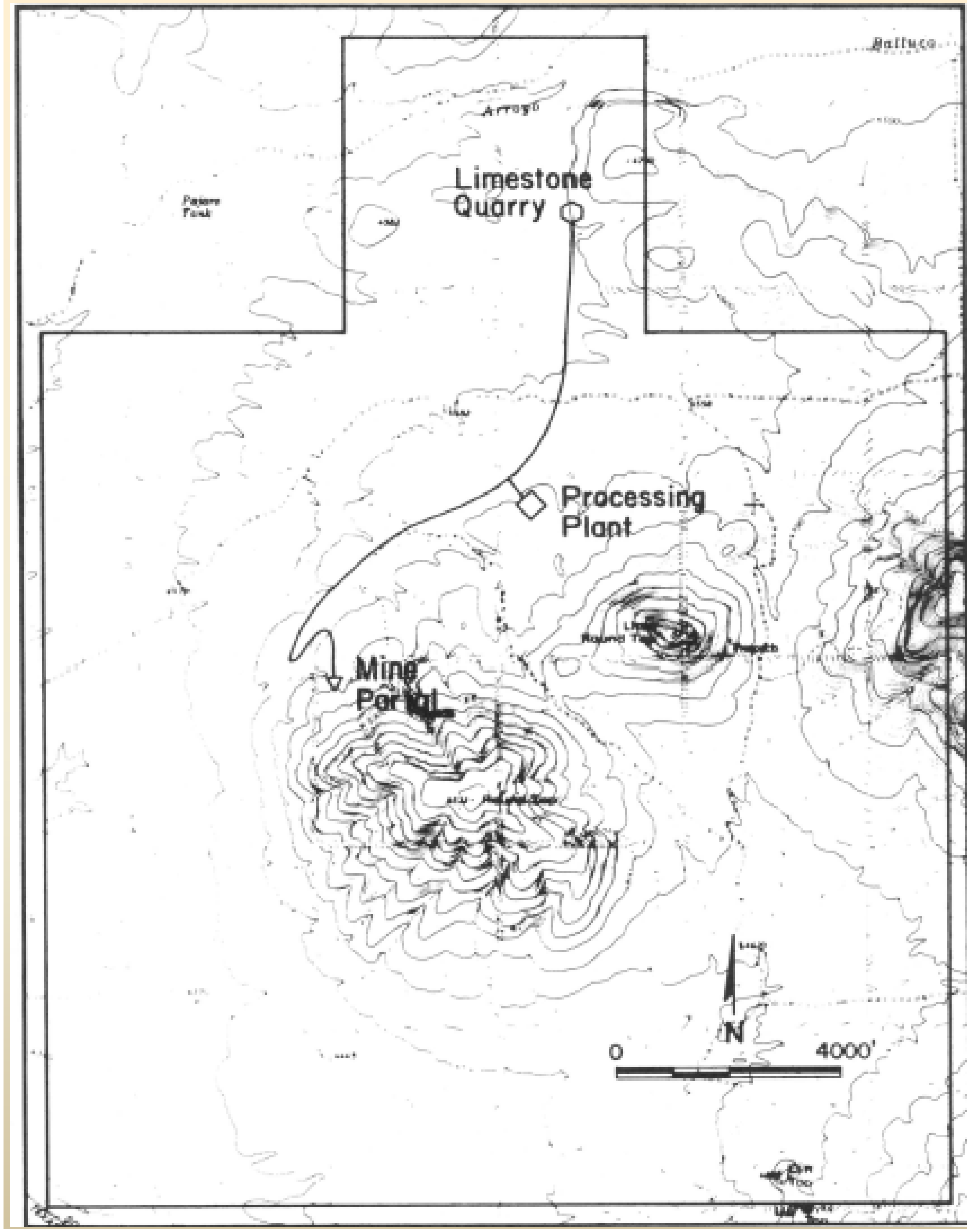
JANUARY 24, 2013

Texas Rare Earth Resources Engages Representative in Order to Explore




INTRUSIVE IGNEOUS ROCKS OF PART OF THE TRANS-PECOS REGION, TEXAS AND NEW MEXICO





Cyprus' Exploration Decline

# Round Top

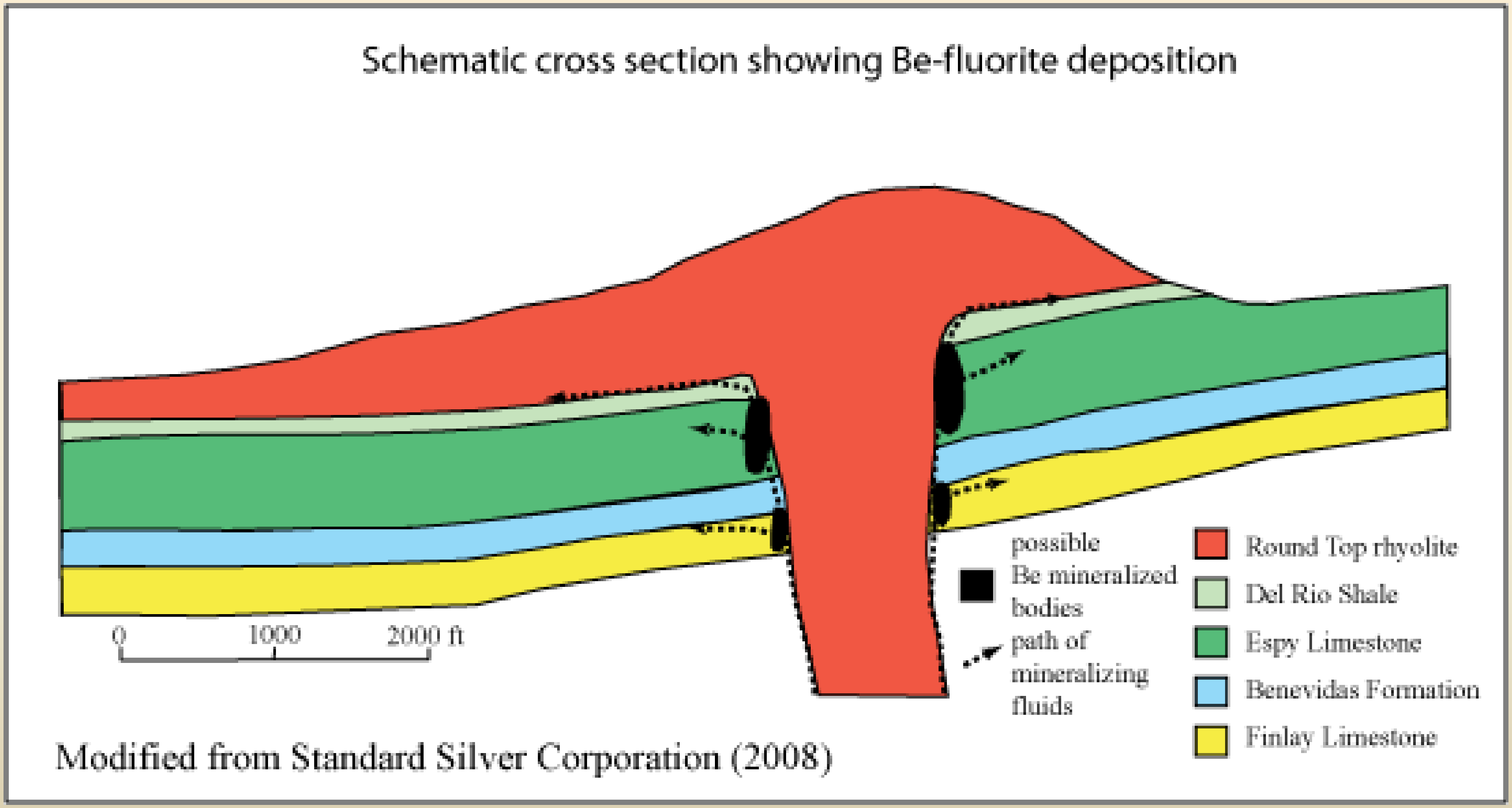
| Round Top Measured + Indicated Mineral Resources | | | | | | |
|---|---|---|---|---|---|---|
| Metric Tonnage 359,150 kt | | | | | | |
| | Element Symbol | gpt | Conversion Factor | Element Oxide | Oxide kg | Oxide % |
| Lanthanum | La | 20.3 | 1.173 | $La_2O_3$ | 8,550,000 | 0.002% |
| Cerium | Ce | 81.0 | 1.171 | $Ce_2O_3$ | 34,064,000 | 0.009% |
| Praseodymium | Pr | 10.4 | 1.17 | $Pr_2O_3$ | 4,369,000 | 0.001% |
| Neodymium | Nd | 28.8 | 1.166 | $Nd_2O_3$ | 12,051,000 | 0.003% |
| Samarium | Sm | 10.5 | 1.16 | $Sm_2O_3$ | 4,391,000 | 0.001% |
| | | | | **Total LREO'** | **63,425,000** | **0.018%** |
| Europium | Eu | 0.20 | 1.158 | $Eu_2O_3$ | 82,000 | 0.000% |
| Gadolinium | Gd | 10.6 | 1.153 | $Gd_2O_3$ | 4,375,000 | 0.001% |
| Terbium | Tb | 3.6 | 1.151 | $Tb_2O_3$ | 1,487,000 | 0.000% |
| Dysprosium | Dy | 31.7 | 1.148 | $Dy_2O_3$ | 13,057,000 | 0.004% |
| Holmium | Ho | 8.0 | 1.146 | $Ho_2O_3$ | 3,307,000 | 0.001% |
| Erbium | Er | 32.8 | 1.143 | $Er_2O_3$ | 13,464,000 | 0.004% |
| Thulium | Tm | 7.1 | 1.142 | $Tm_2O_3$ | 2,903,000 | 0.001% |
| Ytterbium | Yb | 56.5 | 1.139 | $Yb_2O_3$ | 23,114,000 | 0.006% |
| Lutetium | Lu | 8.9 | 1.137 | $Lu_2O_3$ | 3,626,000 | 0.001% |
| Yttrium | Y | 220.9 | 1.269 | $Y_2O_3$ | 100,660,000 | 0.028% |
| | | | | **Total HREOs** | **166,075,000** | **0.046%** |
| | | | | **Total REOs** | **229,500,000** | **0.064%** |

- 44.6 ppm or g/t U content in the Round Top rhyolites
- 298,000 tons of 1.9% Be (historic resource)

# Ore Body - BeO Assay Values

0.1 0.77 5.95 3.7 0.21

# ROUND TOP MOUNTAIN, SIERRA BLANCA, TEXAS

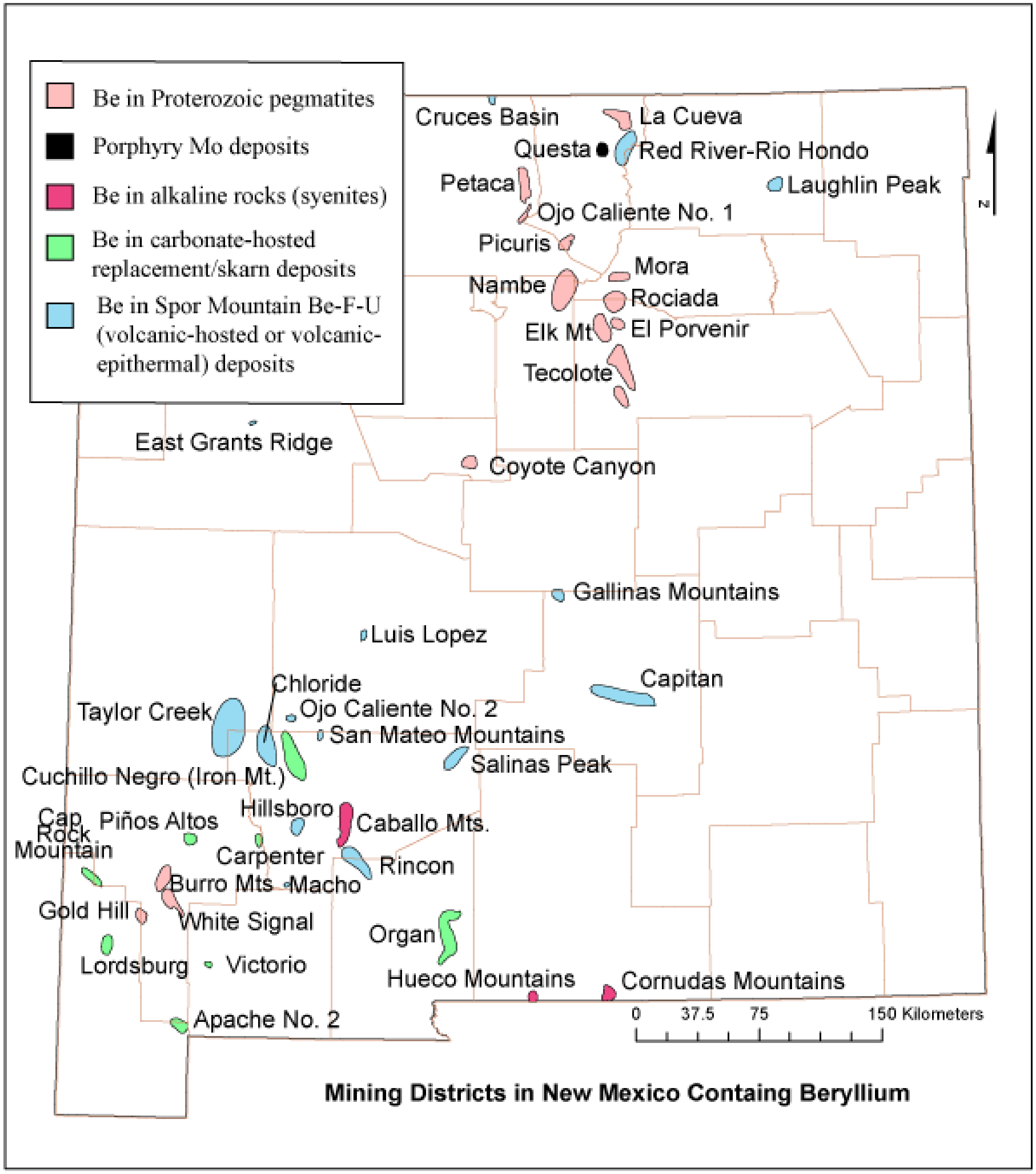


Red Rhyolite containing Rare Earth Minerals, Round Top, North Side
Image 27 of 36

CLOSE ✕

**Mineralized Contact between Sedimentary Rock & Rhyolite, Round Top, North Side**
Image 9 of 12

CLOSE ✕




Mining districts in New Mexico that contain beryllium (Be). More details are in McLemore (2010).

# Apache Warm Springs deposit, Socorro County, New Mexico

# BE Resources Inc.

"continues to search for a suitable new project for the Company and to review its options for its New Mexico beryllium project which has been placed on care and maintenance."

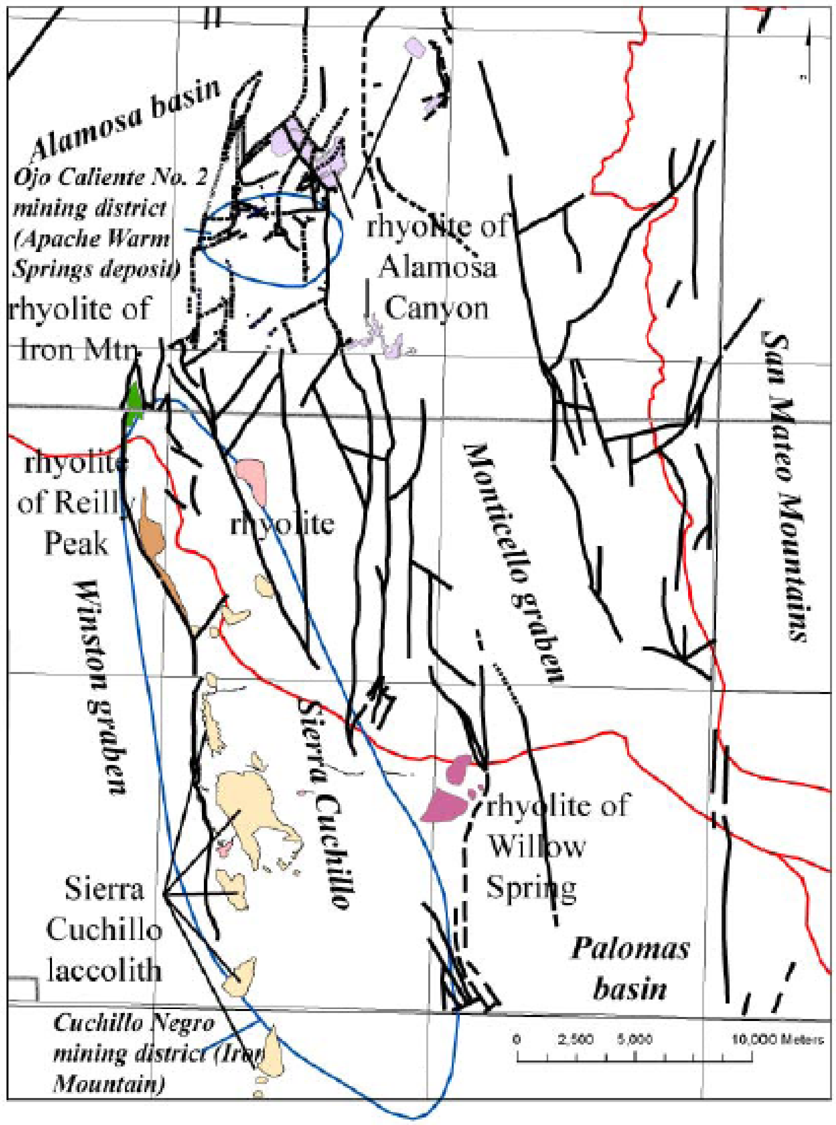
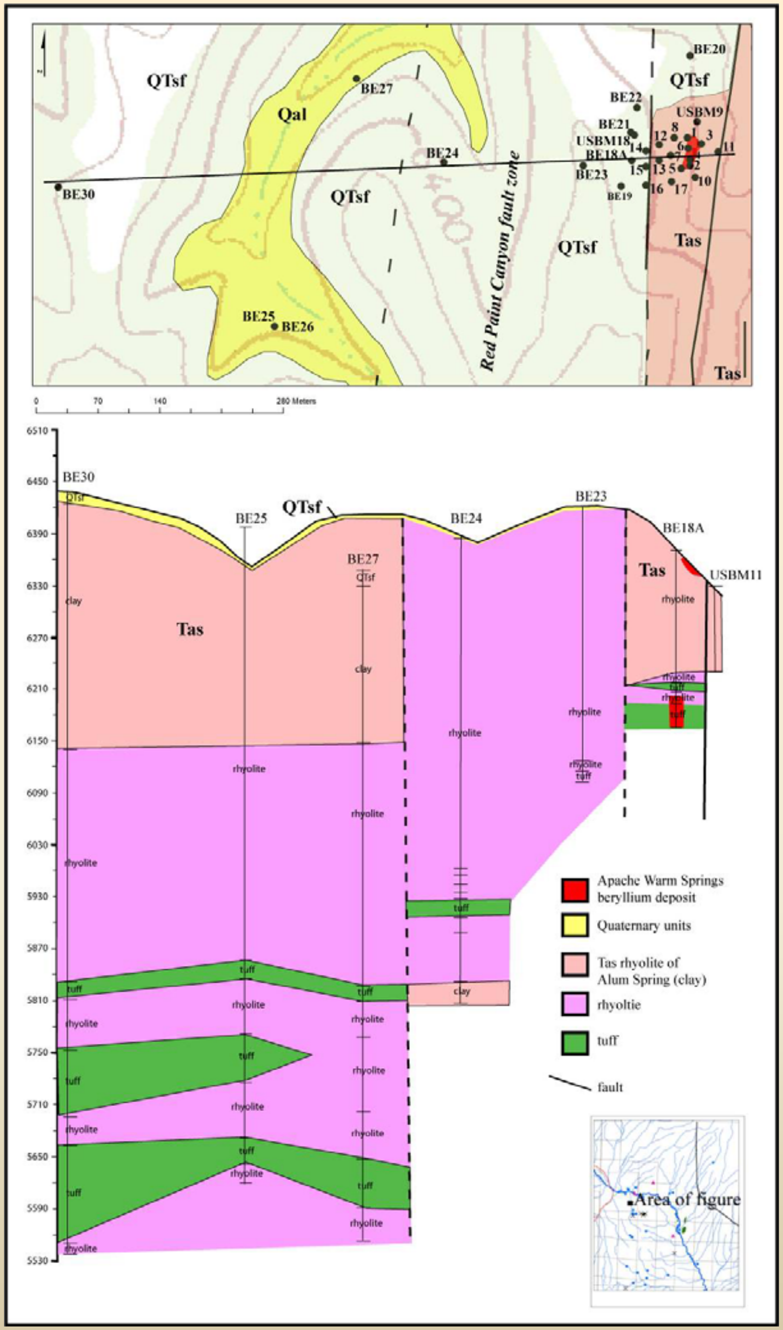
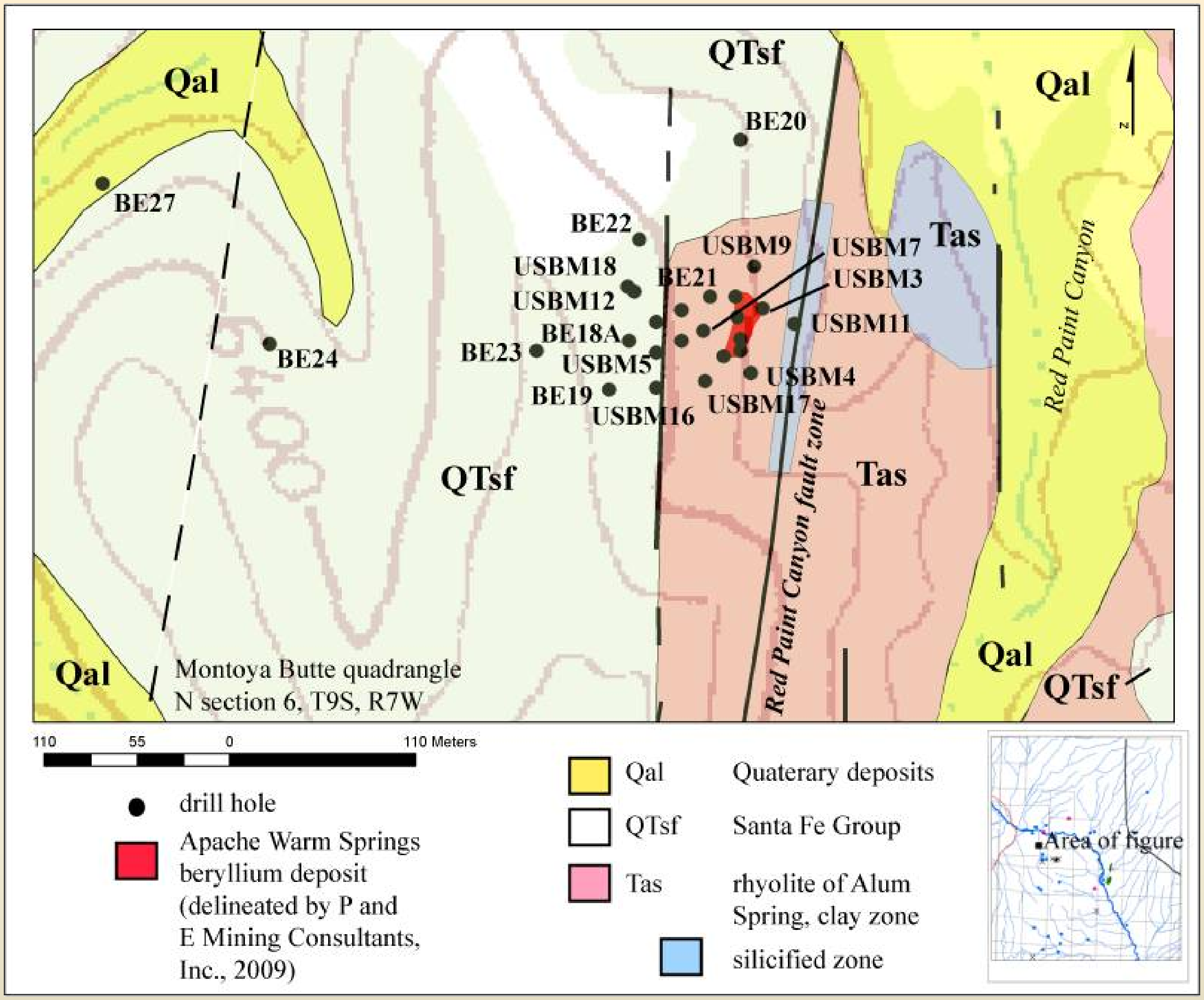



FIGURE 10. Regional structure map of the Sierra Cuchillo-San Mateo area showing the mining districts (blue) in the area (defined by McLemore, 2010a). Red line is boundary of Alamosa basin. Major granitic-rhyolite intrusions are shown in colored polygons and discussed in text. Not all rhyolite intrusions in the San Mateo Mountains are shown. Black lines are faults from Osburn (1984), Harrison (1992), Jahns et al. (2006), Ferguson et al. (2007), and McLemore (2010a).




Geologic map and cross section of the Apache Warm Springs beryllium deposit and adjacent area (N section 6, T9S, R7W). Interpretations are by the author from examination of drill cuttings, using available drill data (McLemore, 2010a), and surface mapping.

Apache Warm Springs beryllium deposit (Be), as delineated by P and E Mining Consultants, Inc. (2009) as determined from trenching and drilling, looking northeast (N section 6, T9S, R7W).




Alteration map of the Apache Warm Springs beryllium deposit. The western fault (between BE27 and BE 24) is identified from drilling data (McLemore, 2010a).

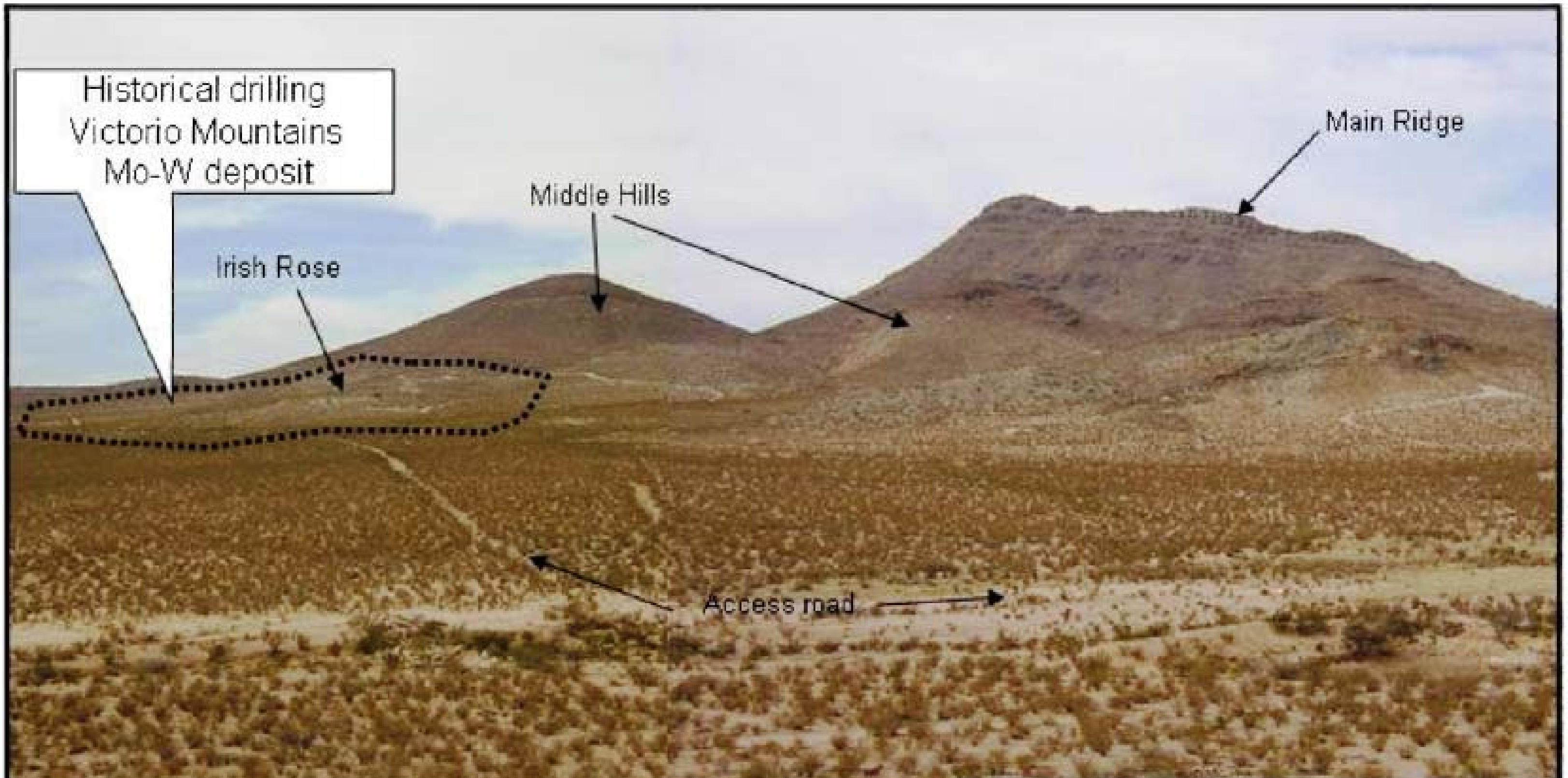
Clay zone with red hematite-kaolinite and white kaolinite surrounding the Apache Warm Springs beryllium deposit (N section 6, T9S, R7W). A sample collected from the site shown on the left contains kaolinite, quartz, and hematite (Mont-35, McLemore, 2010a).

A sample collected from the white clay shown in the photograph on the right contains quartz, kaolinite, illite, smectite and mixed layered clays (Mont-61, McLemore, 2010a).

Silicified zone, looking southwest. The Apache Warm Springs beryllium deposit is to the right (N section 6, T9S, R7W).

# Porphyry molybdenum (±tungsten) deposits and Carbonate-hosted replacement and skarn deposits

# Victorio Mountains, New Mexico




View looking NW from Mine Hill toward Middle Hills and Mo-W deposit

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## PROJECTS

Victorio

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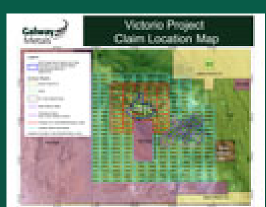
Property Location Map




Claims Location Map

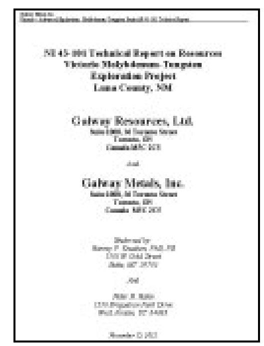
## VICTORIO

The Victorio Molybdenum-Tungsten Project is an advanced-stage exploration property in which Galway Metals has an option to acquire a 100% interest. Significant activity at Victorio has been inactive since the early 1980's due to depressed metal pricing. The property has favorable infrastructure such as access by paved road to within a few miles of the site, a nearby railway and a gas pipeline. Victorio is located approximately 20 miles west of Deming, New Mexico, in Luna County.

In 2008, Galway completed a 12-hole, 25,000 foot, phase 2 infill drilling program. The purpose of the infill drilling program was to upgrade the resources with the next step being a pre-feasibility study. The first phase of drilling included 6 holes totaling 13,000 feet. This project was acquired in June 2006, and was worked on extensively by Gulf Minerals in the early eighties as they drilled 165,000 feet.

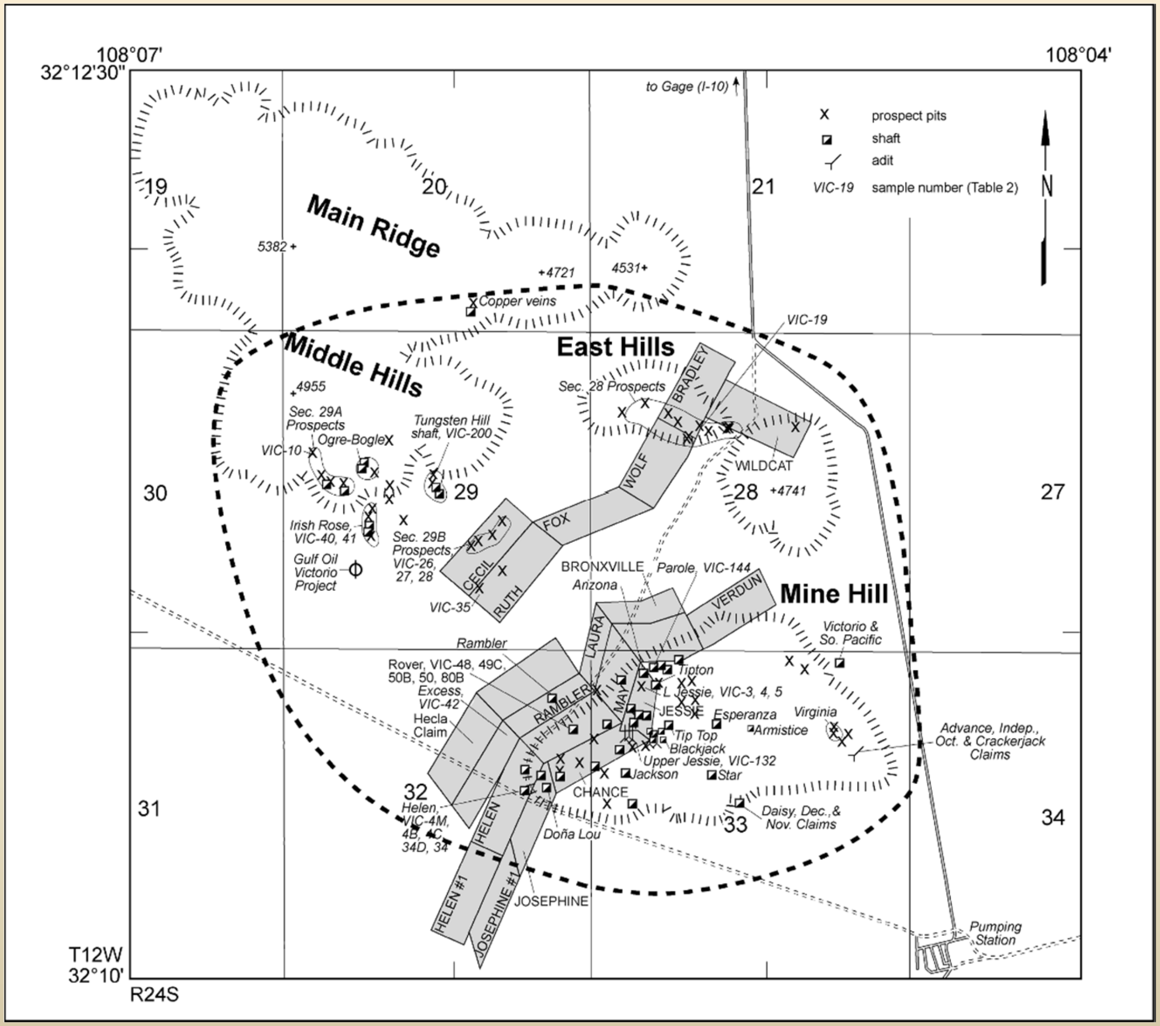
The current Technical Report on Victorio's Resources by Dr. H. Peter Knudsen and Peter H. Hahn dated November 15, 2012, was derived from 217,000 feet of drilling using an $8.00 Tungsten and $15.00 per pound molybdenum long term price.

Video for the Victorio Project

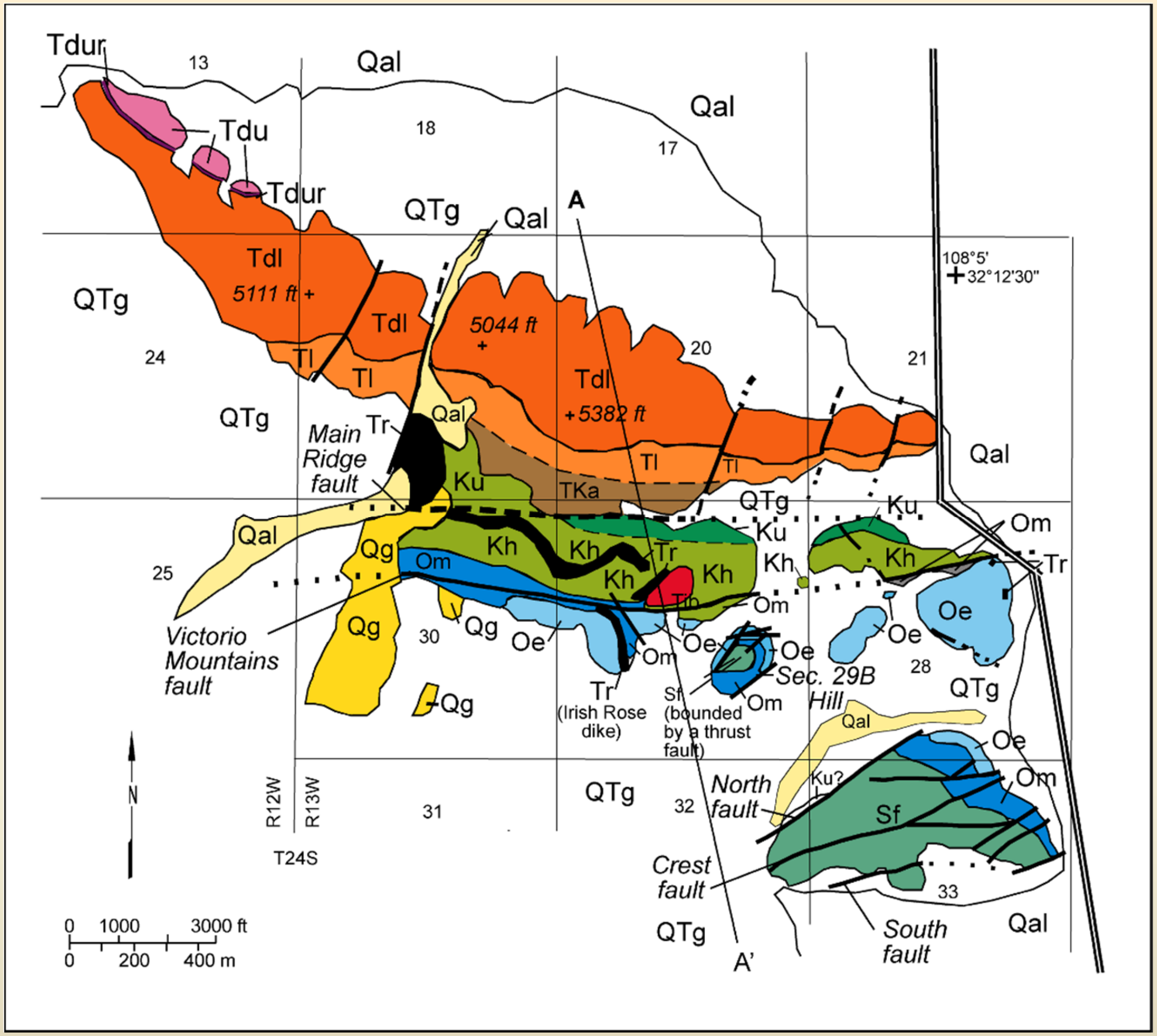


NI 43-101 Technical Report on Resources November 15, 2012

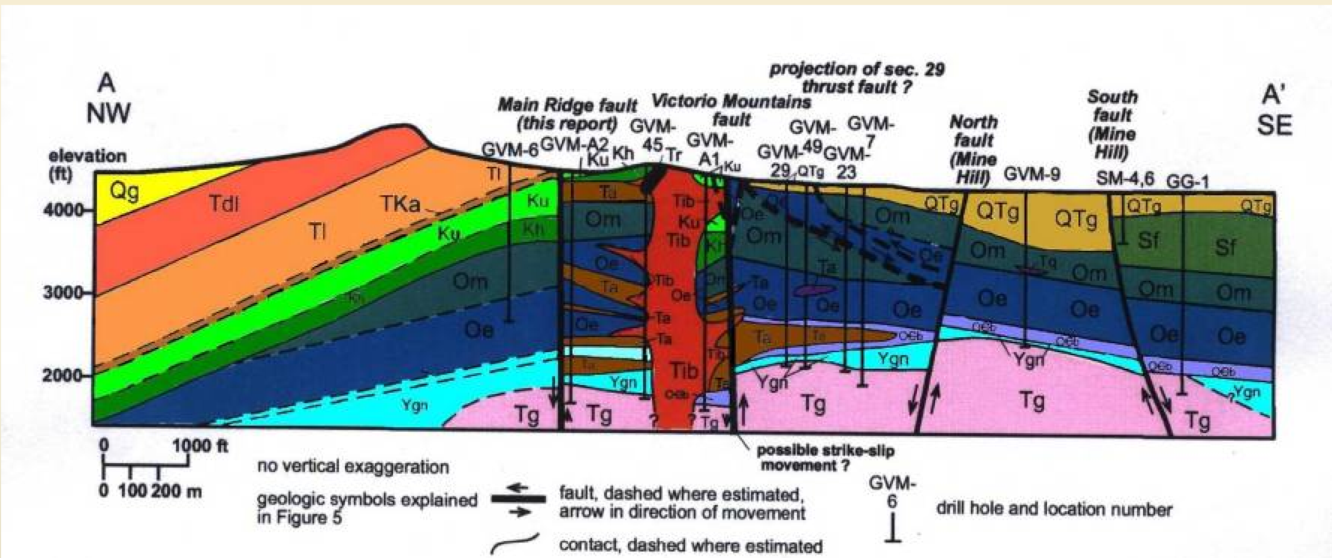
# Mines and prospects in the Victorio mining district, Luna County.



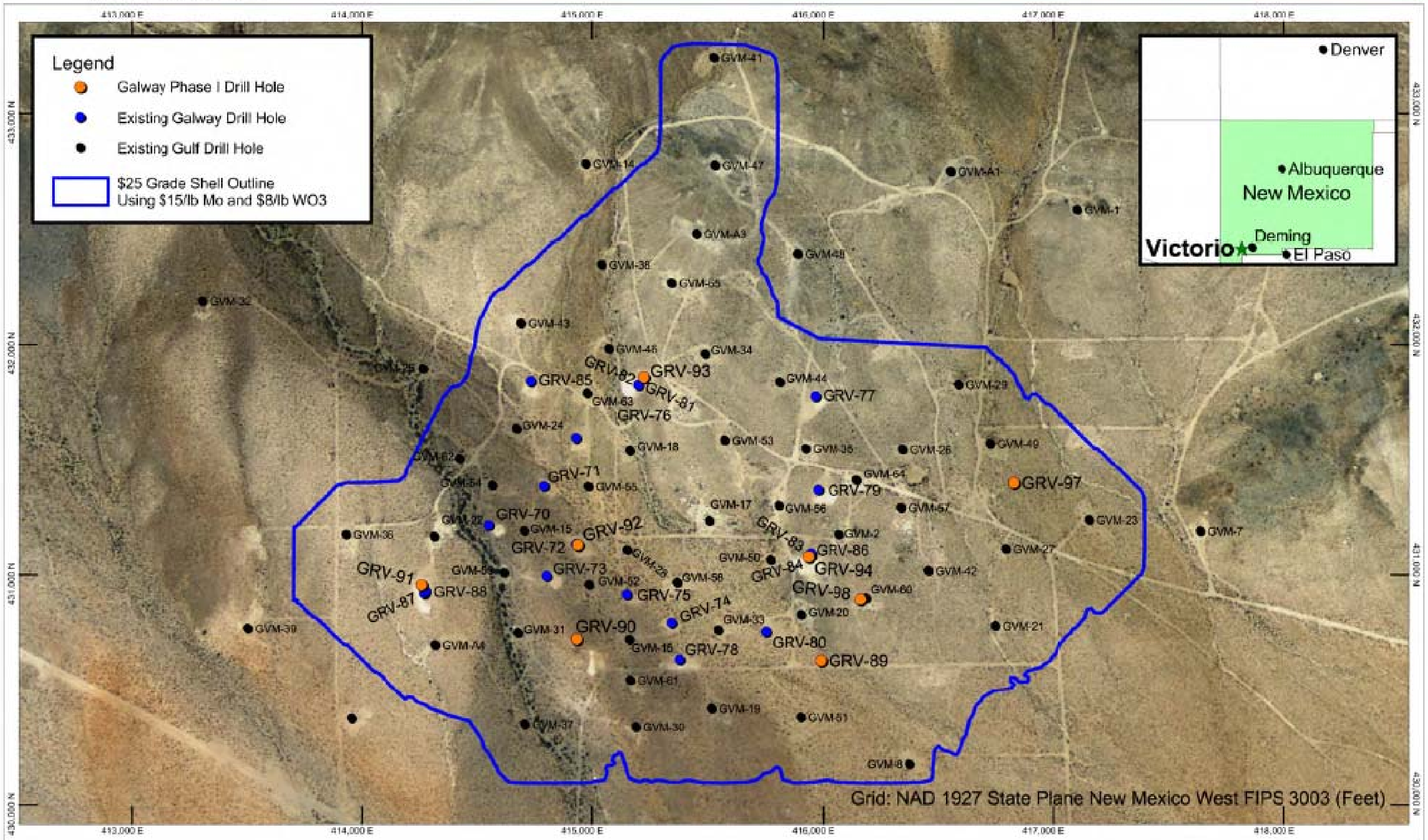
Simplified geologic map of the Victorio Mountains (modified from Kottlowski, 1960; Thorman and Drewes, 1980; unpublished mapping by Gulf Resources, Inc.; unpublished mapping by V. T. McLemore).



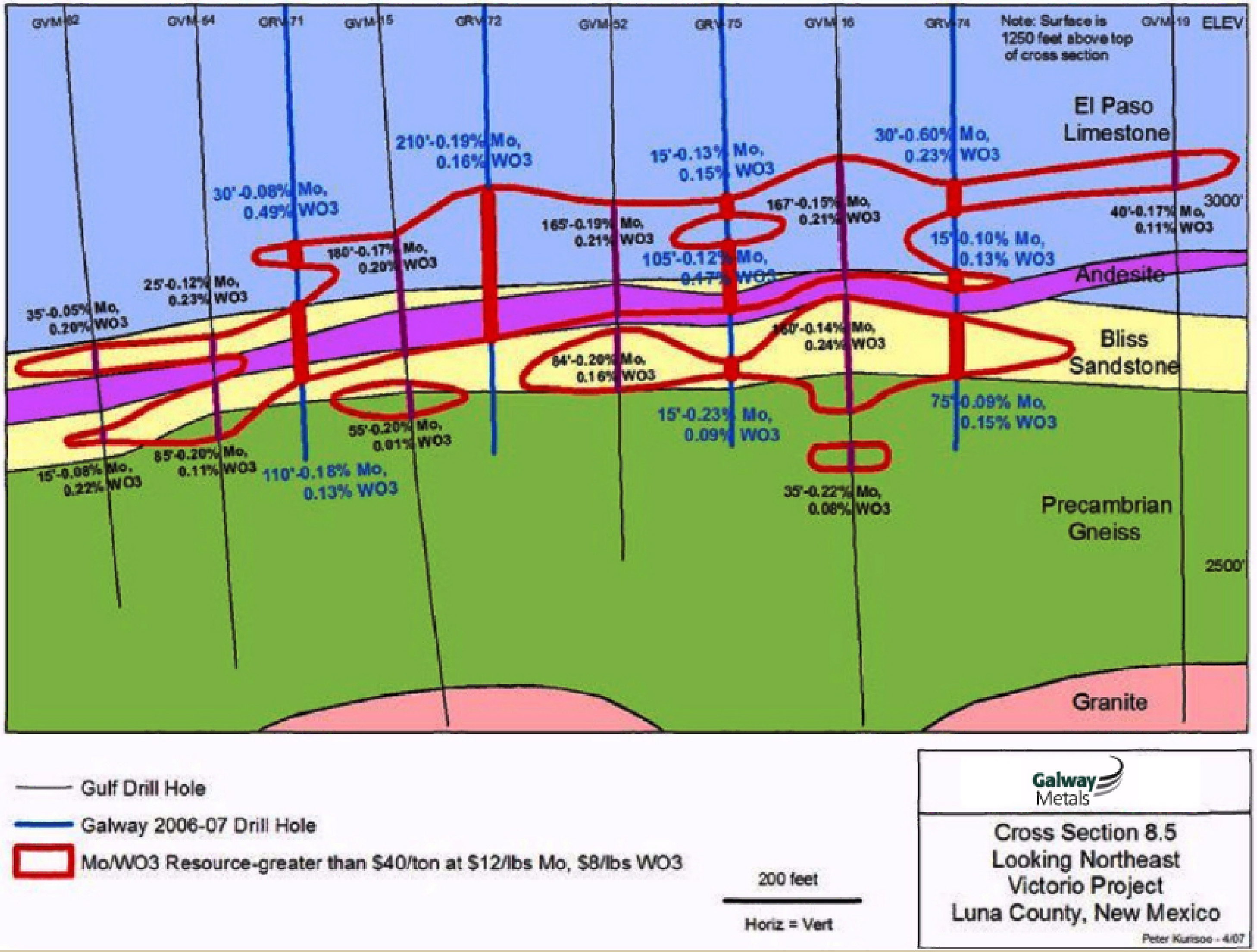

# Simplified cross section of the Victorio Mountains (modified from company drill data and unpublished mapping by K. Donahue and V.T. McLemore). Some of the drill holes are projected onto the cross section.

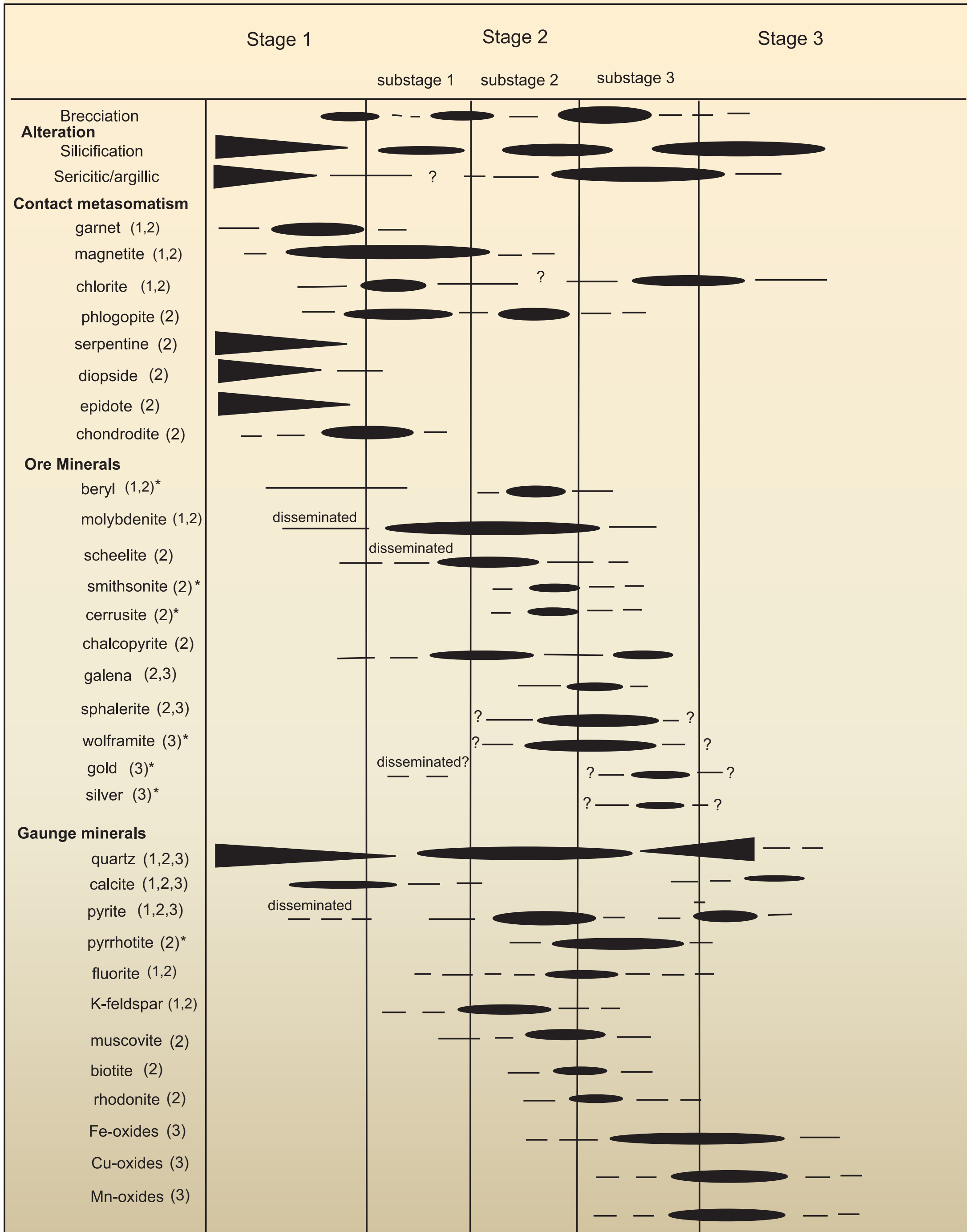



# Victorio Project
# Drill Hole Location Map



# Victorio - Thick Ore Intercep

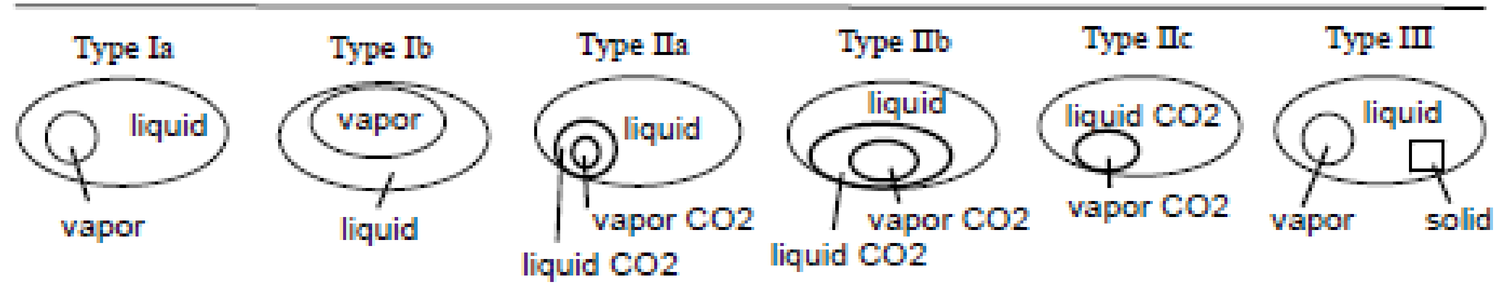





Relative paragenetic sequence for the Victorio mining district showing the mineral relationships and alteration events (from Donahue, 2002). The paragenetic sequence is for all three types of deposits. 1 = porphyry Mo , 2 = skarn, 3 = carbonate-hosted replacement deposit,

TABLE 9. Summary of all fluid inclusion results. Figure below illustrates the classification used to identify the fluid inclusion type (From Donahue, 2002).

| Deposit | Type | Size Range micron (µ) | Th range degrees | Th ave degrees | Salinity range eq. wt% NaCl | Salinity ave eq. wt% NaCl |
|---|---|---|---|---|---|---|
| Carbonate-hosted replacement | Ia, IIa, IIb, IIc | <2-15 | 109 - 350 | 213 | 0.8 - 19.3 | 8.8 |
| Mine Hill siliceous veins | Ia, IIa, IIb, IIc | <2-10 | 109 - 350 | 217 | 0.8 - 4.1 | 2.1 |
| E109 non-oxidized | Ia | <2-5 | 151 - 257 | 209 | 10.2 - 19.3 | 12.9 |
| Skarn | Ia, Ib, IIa, IIb, III | <2-40 | 171 - 360 | 242 | 0.02 - 25.6 | 6.6 |
| Barren qtz veins | Ia, Ib, IIa, IIb | <2-40 | 199 - 340 | 278 | 3.1 – 10.9 | 5.9 |
| Porphyry | Ia, Ib, IIa, IIb | <2-10 | 179 - 325 | 255 | 2.0 - 11.2 | 6.1 |



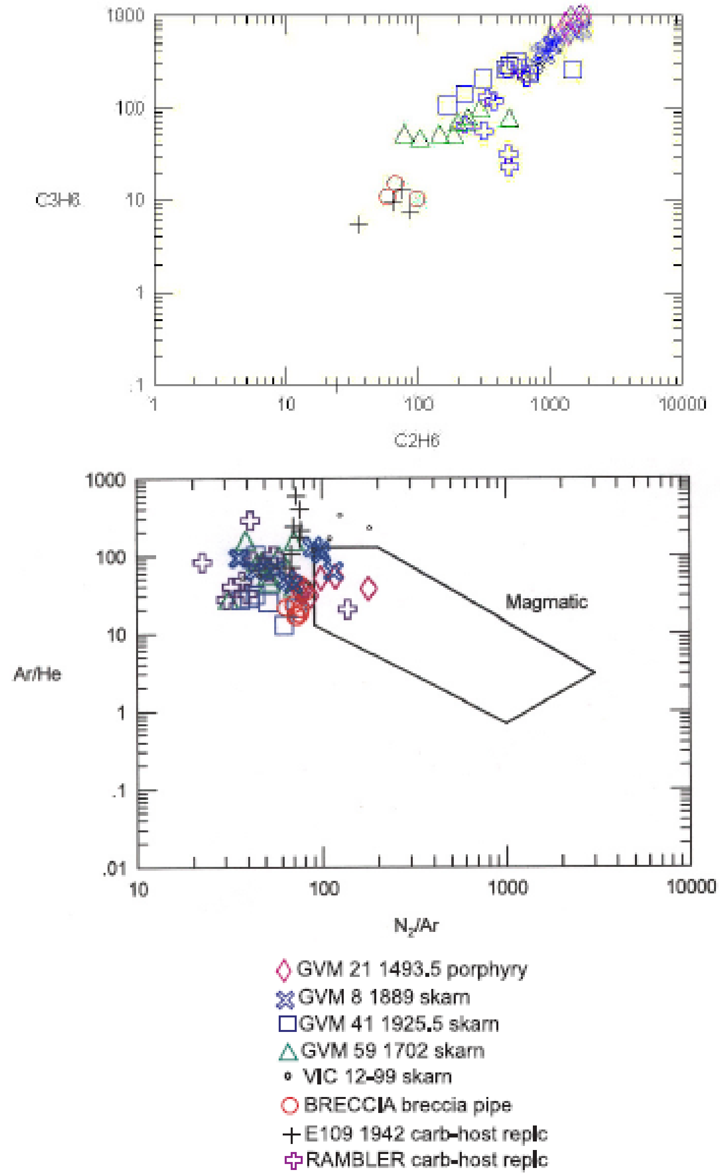
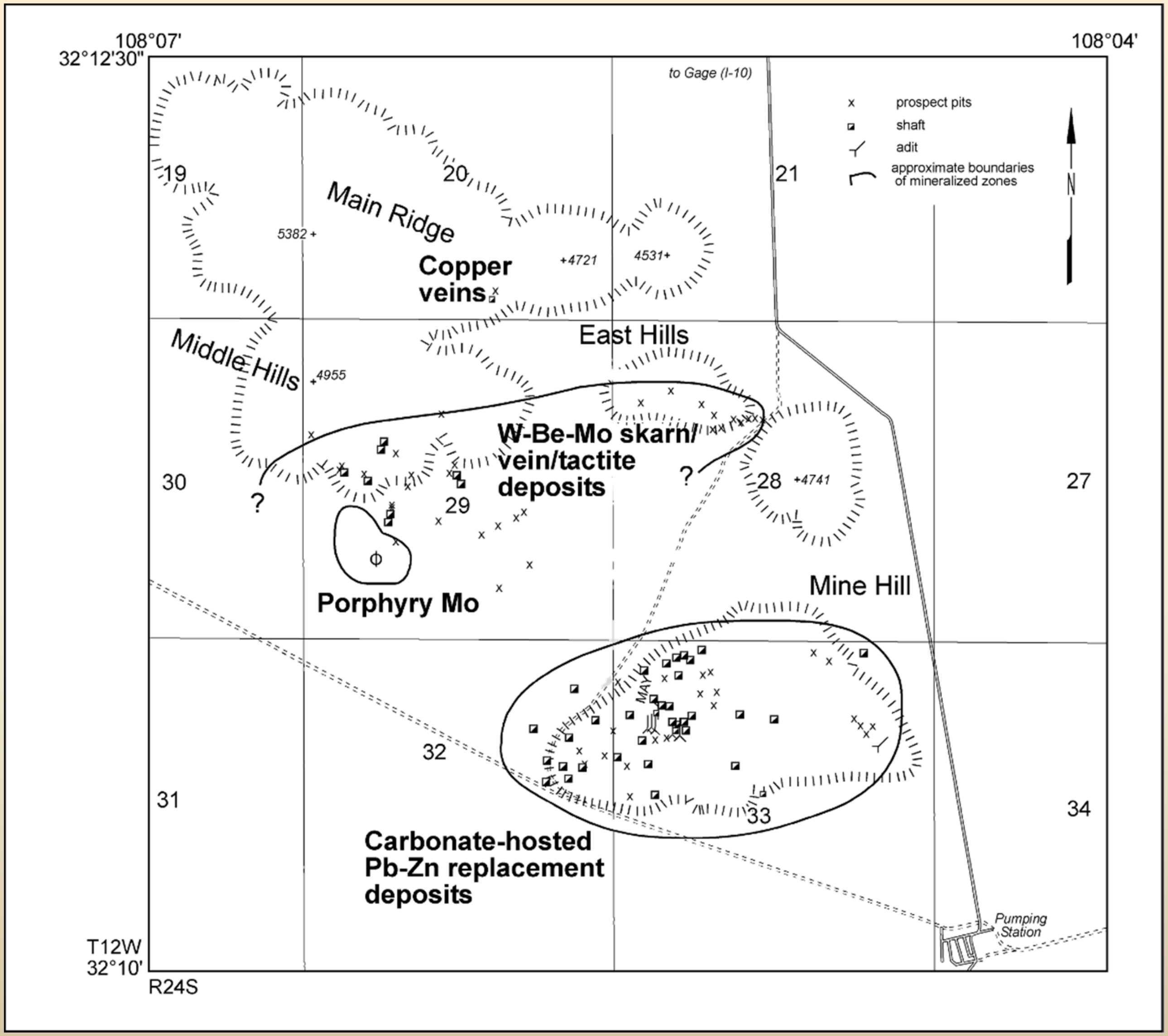



FIGURE 19. Fluid inclusion gas analysis results showing the possible origins of the fluids, the majority of the Victorio samples fall on the boundary and just outside the

# Mineral zonation in the Victorio Mountains mining district.



Victorio Resource Estimate using $15/lb molybdenum and $8/lb Tungsten

| Category | Cutoff/ Ton | Tons | Mo % | Tungsten % | Contained Metal (pounds) | |
|---|---|---|---|---|---|---|
| | | | | | Molybdenum | Tungsten |
| Measured | $25 | 37,737,913 | 0.10 | 0.08 | 71,702,035 | 61,890,177 |
| Indicated | $25 | 39,499,463 | 0.08 | 0.09 | 64,779,119 | 72,679,012 |
| **M+I** | **$25** | **77,237,376** | **0.09** | **0.09** | **136,481,154** | 134,569,189 |
| Inferred | $25 | 77,222,232 | 0.07 | 0.09 | 114,288,903 | 143,633,352 |
| | | | | | | |
| Measured | $35 | 20,275,366 | 0.12 | 0.11 | 47,444,356 | 42,983,776 |
| Indicated | $35 | 19,125,184 | 0.10 | 0.12 | 39,397,879 | 45,517,938 |
| **M+I** | **$35** | **39,400,550** | **0.11** | **0.11** | **86,842,235** | 88,501,714 |
| Inferred | $35 | 34,728,550 | 0.10 | 0.11 | 66,678,816 | 78,486,523 |

# Also Be

# Arizona

- Be along fractures in granite mined from Beryl Hill and Live Oak mines in 1950s in the Dos Cabezas Mountains
- Tungsten veins in Yuma and Graham Counties
- Pegmatites
  - Kingman, Mohave County
  - Bradshaw Mountains, Yavapai County

# AGS Bull 180

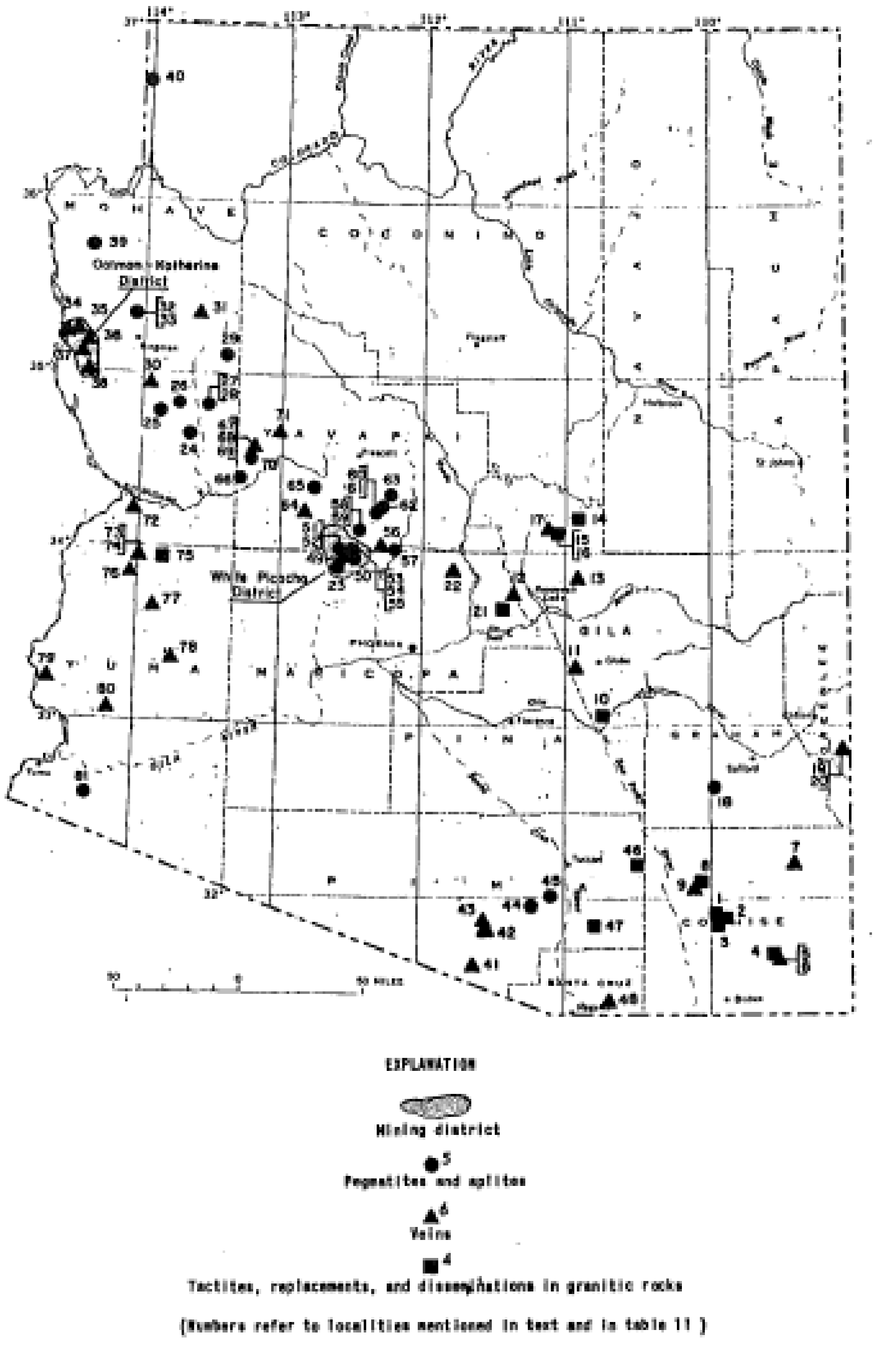
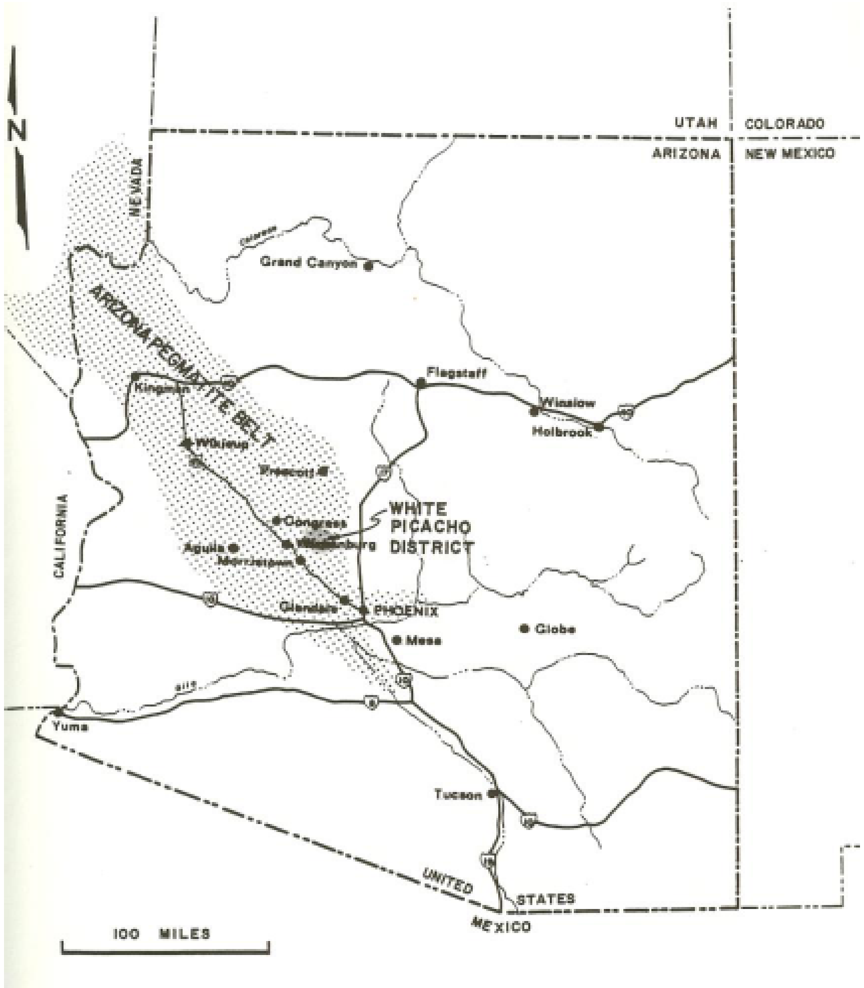



FIGURE 16.—Beryllium in Arizona.




| | | Be PPM | Bi PPM | Cs PPM | Ga PPM | Li PPM | Rb PPM | Ta PPM |
|---|---|---|---|---|---|---|---|---|
| 5.26.10.1 | Morning Star* | 1.21 | 0.27 | 1.22 | 2.27 | 7.5 | 21.4 | <0.01 |
| 5.26.10.2 | Do.* | 0.96 | 3.53 | 2.43 | 1.46 | 3.3 | 18.7 | <0.01 |
| 5.26.10.3 | Do. | 2.35 | 0.21 | 35.5 | 8.29 | 113.5 | 610 | 1.92 |
| 5.26.10.4 | Do. | 1.69 | 0.32 | 78.9 | 14.5 | 75 | 1840 | 2.55 |
| 5.26.10.5 | Sunset | 26.7 | 0.64 | 99 | 36.6 | 24.5 | 890 | 17.3 |
| 5.26.10.6 | Do. | 4.08 | 0.81 | 4.98 | 7.67 | 150 | 88.6 | 1.66 |
| 5.26.10.7 | Do. | 13.6 | 1.52 | 19.95 | 30.6 | 74.3 | 510 | 1.89 |
| 5.26.10.8A | Lower Jumbo | 30 | 1.23 | 457 | 71.9 | 156 | 3000 | 3000 |
| 5.26.10.8B | Do. | 3.05 | 0.53 | 76.9 | 137 | 21100 | 560 | 200 |
| 5.26.10.8C | Do. | 2.99 | 1.58 | 214 | 87.1 | 7680 | 1350 | 4200 |
| 5.26.10.8D | Do. | 3.21 | 0.19 | 369 | 74.1 | 5100 | 2850 | 300 |
| 5.26.10.8E | Do. | 2.26 | 0.68 | 468 | 60.1 | 5630 | 3220 | 1400 |
| 5.26.10.8F | Do. | 2.67 | 4.72 | 4.75 | 33.9 | 223 | 70.2 | 4.74 |
| 5.26.10.9 | Sunrise | 67.9 | 442 | 26.2 | 20.8 | 33 | 244 | 11.4 |
| 5.26.10.10 | Do. | 43.7 | 1.51 ? | | 79.4 | 11900 | 6990 | 500 |
| 5.26.10.11 | Do. | 67.8 | 29.5 | 9.86 | 32 | 122 | 88.2 | 61 |
| 5.26.10.12 | Do. | 5.18 | 0.6 | 75.6 | 17.65 | 134.5 | 790 | 12.35 |
| 5.26.10.13 | Unnamed | 203 | 84.9 | 63 | 55 | 232 | 500 | 34.6 |
| 5.26.10.14 | Do. | 2.29 | 0.38 | 2.72 | 14.2 | 38.8 | 169.5 | 1.52 |
| 5.27.10.8 | Buckhorn | 1.44 | 0.08 | 5.72 | 18.4 | 17.3 | 206 | 3.59 |

6 INCHES

# GRADE-TONNAGE NON-PEGMATITE

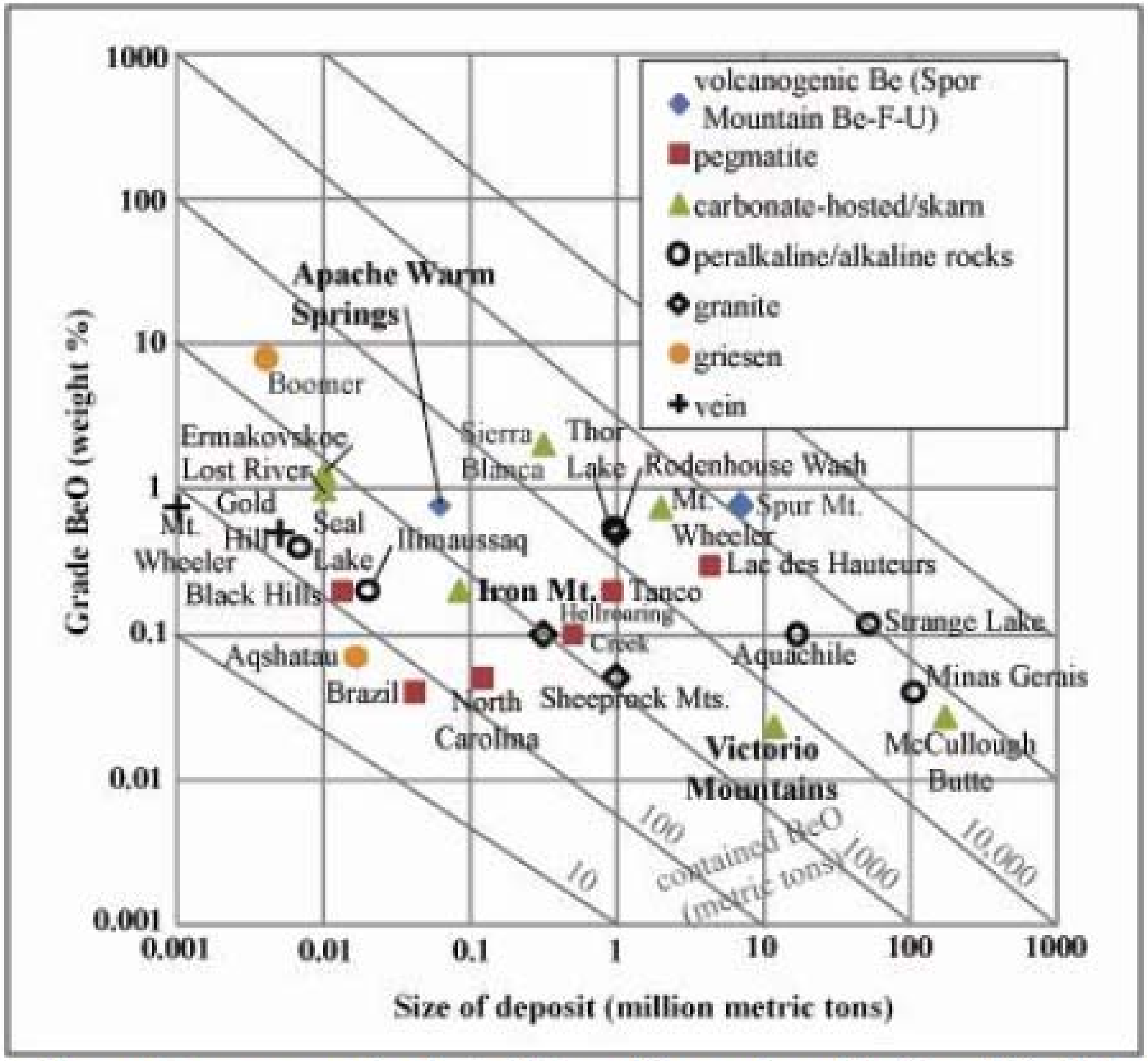



FIGURE 5. Grade and tonnage of selected beryllium deposits (modified from Barton and Young, 2002 using references in Table 1). Deposits in bold are located in New Mexico. See Table 1. Note that size of deposits includes production and reserves/resources and are not always NI 43-101 compliant and subject to change.

# Pegmatites

# Pegmatites

- “an essentially igneous rock, commonly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse but variable grain-size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth-habits.” (London, 2008)
- Products of magmatic differentiation, residual parts of the magma
- Increased volatiles and incompatible elements (large ionic radii)

# Pegmatites

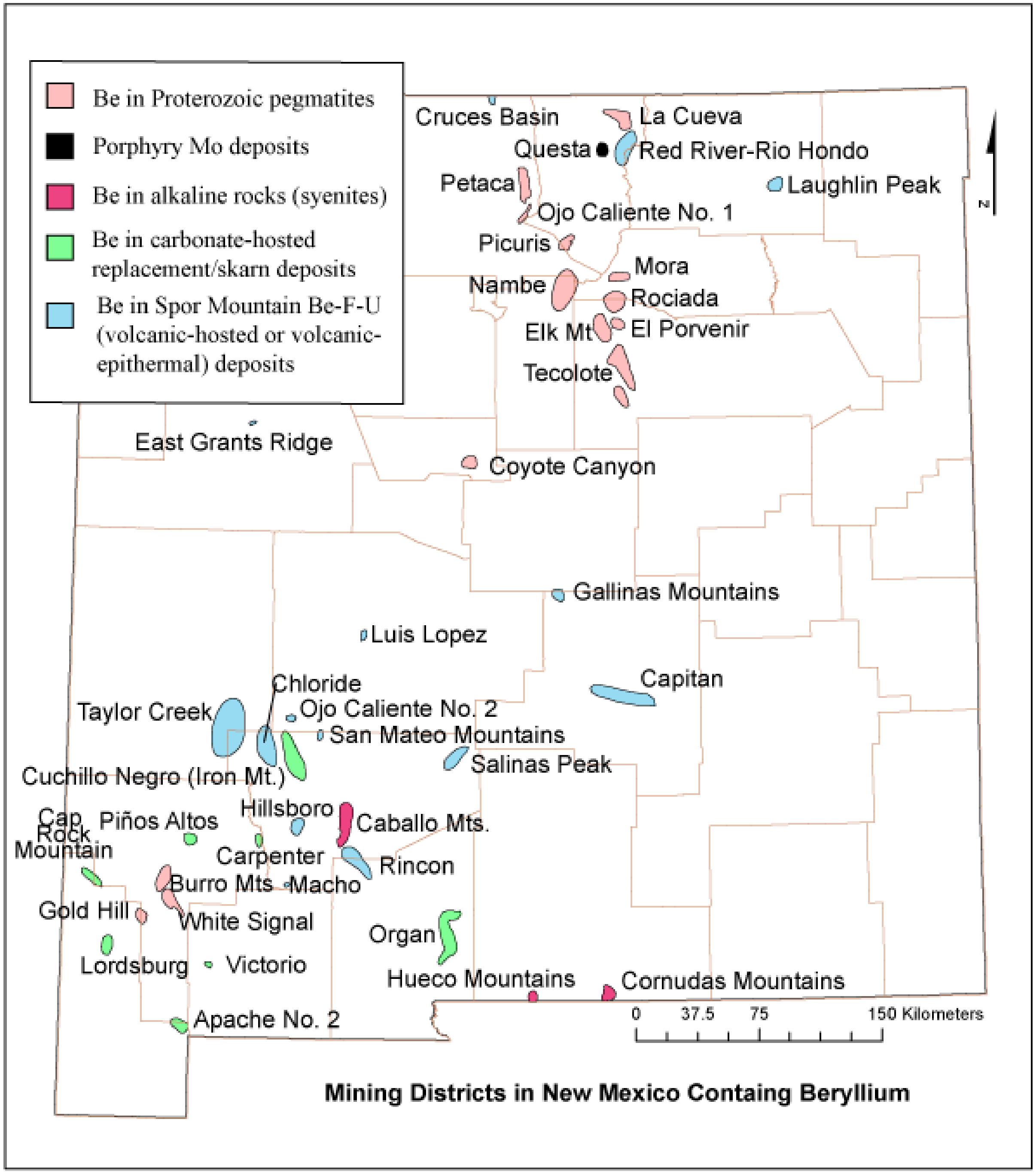
- Dikes, sills, veins, irregular masses
- In part due to slow cooling
- Grade into aplites, which formed if the magma losses suddenly the volatiles and only small crystals grow
- mostly due to large volumes of gases (volatiles =H2O, Cl, F)
  – Make it difficult for crystals to form=fewer crystals
  – Makes the normally sticky granitic magma more viscous, which allows for elements to move around
  – Volatiles separate as bubbles surrounded by normal liquid magma and crystals can form from both

# Types

- Acidic pegmatites or granitic pegmatites
- Syenitic pegmatites (Na rich with little quartz)
- Basic and ultrabasic (feldspar, olivine, amphibole, biotite)


**Figure 1.** World map showing the locations of LCT pegmatite deposits or districts, including smaller districts in the United States. The symbols are color-coded by age. Giant deposits are represented by larger symbols.

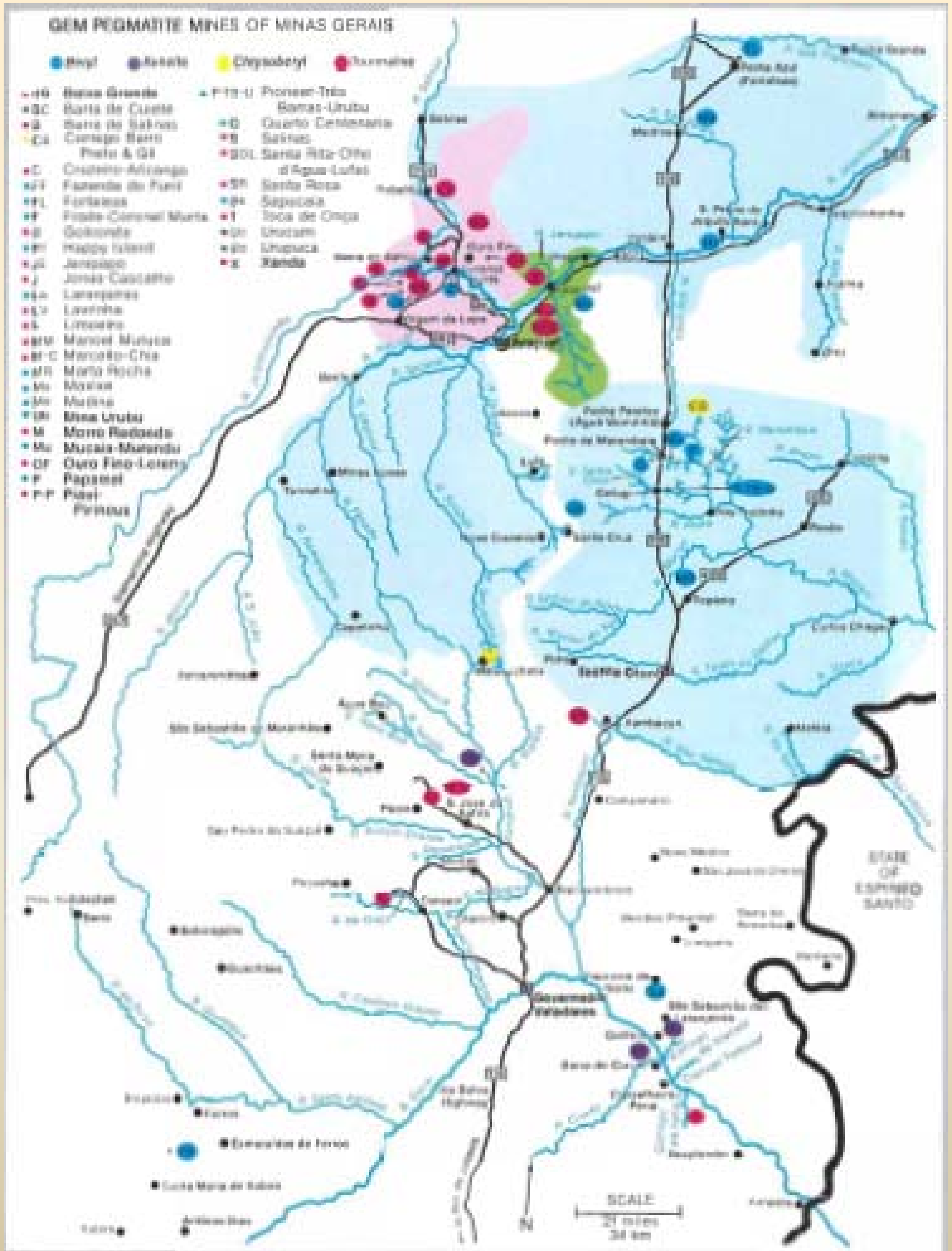
USGS OF13-1008



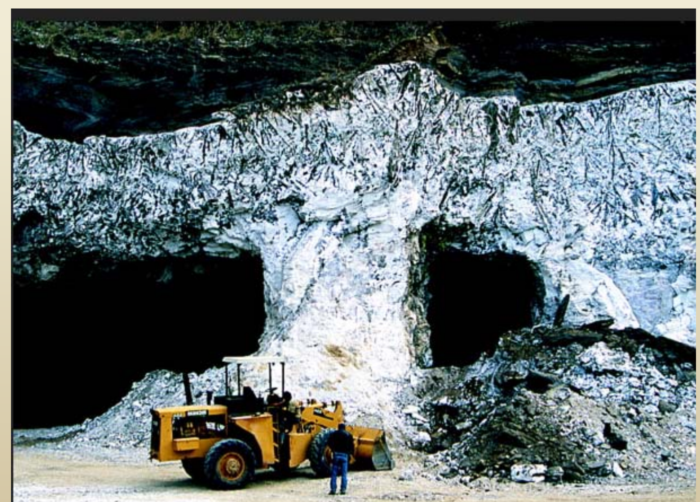

Mining districts in New Mexico that contain beryllium (Be). More details are in McLemore (2010).

TABLE 4. Beryllium production from Proterozoic pegmatites in New Mexico (Meeves et al., 1966). Additional production in 1963-1969 is withheld. Additional production from Iron Mountain in the Cuchillo Negro district, Santa Fe district, and Mora district is unknown.

| County | Year | Beryl (pounds) |
|---|---|---|
| Rio Arriba | 1951-1963 | 12,748 |
| San Miquel | 1951-1963 | 49,015 |
| Taos | 1951-1963 | 1,678,054 |
| Harding, Taos | 1950-1959 | 1,696,600 |
| TOTAL | 1950-1963 | 1,739,817 |




# Minas Gerais, Brazil (Proctor, 1984)

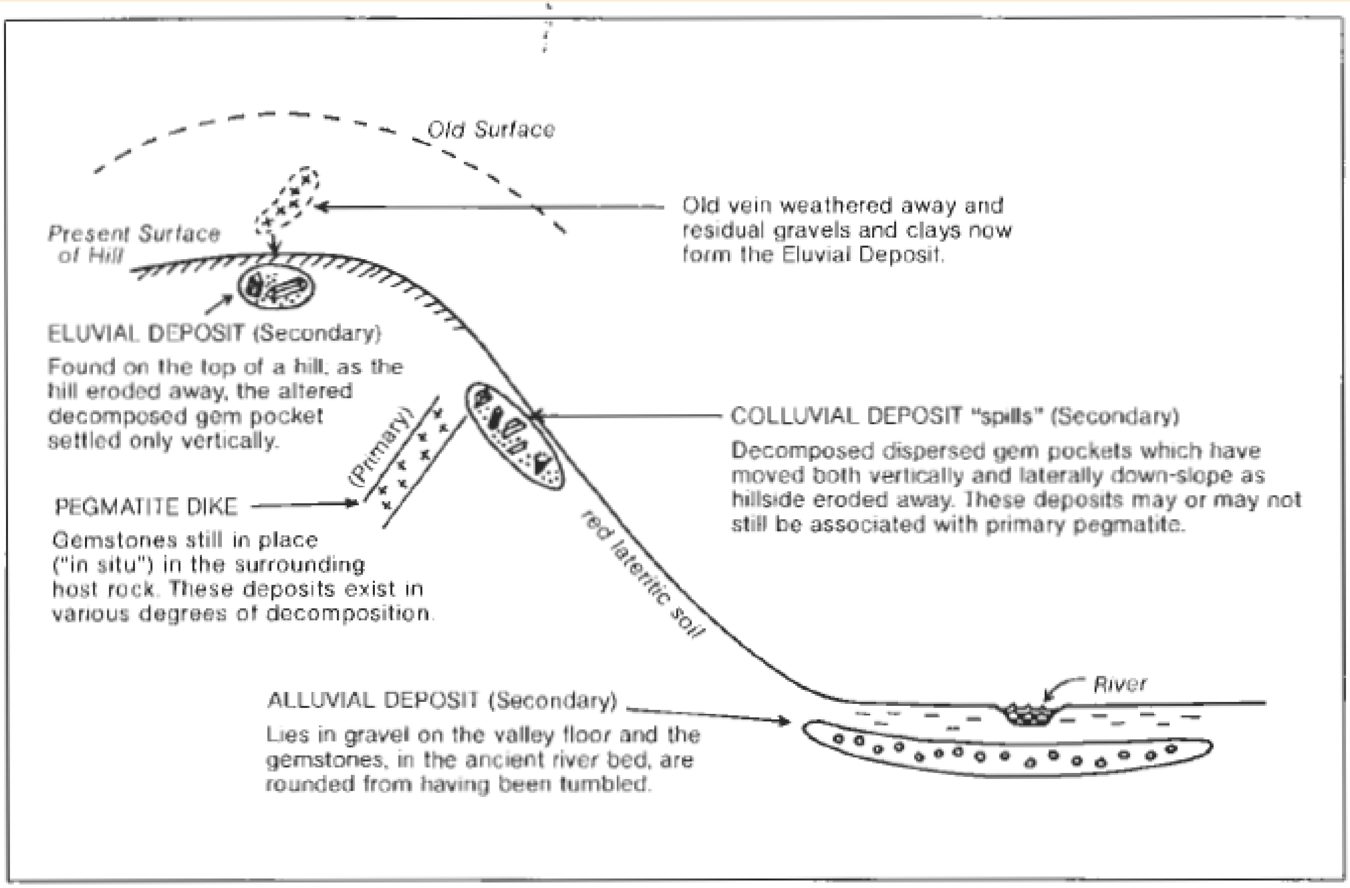



*Figure 4. Diagram of primary (pegmatite dike) and secondary (eluvial, colluvial, and alluvial) deposits. All three secondary deposits have traveled some distance from their original primary pegmatite.*

Minas Gerais, Brazil (Proctor, 1984)

Brazilian Aquamarine

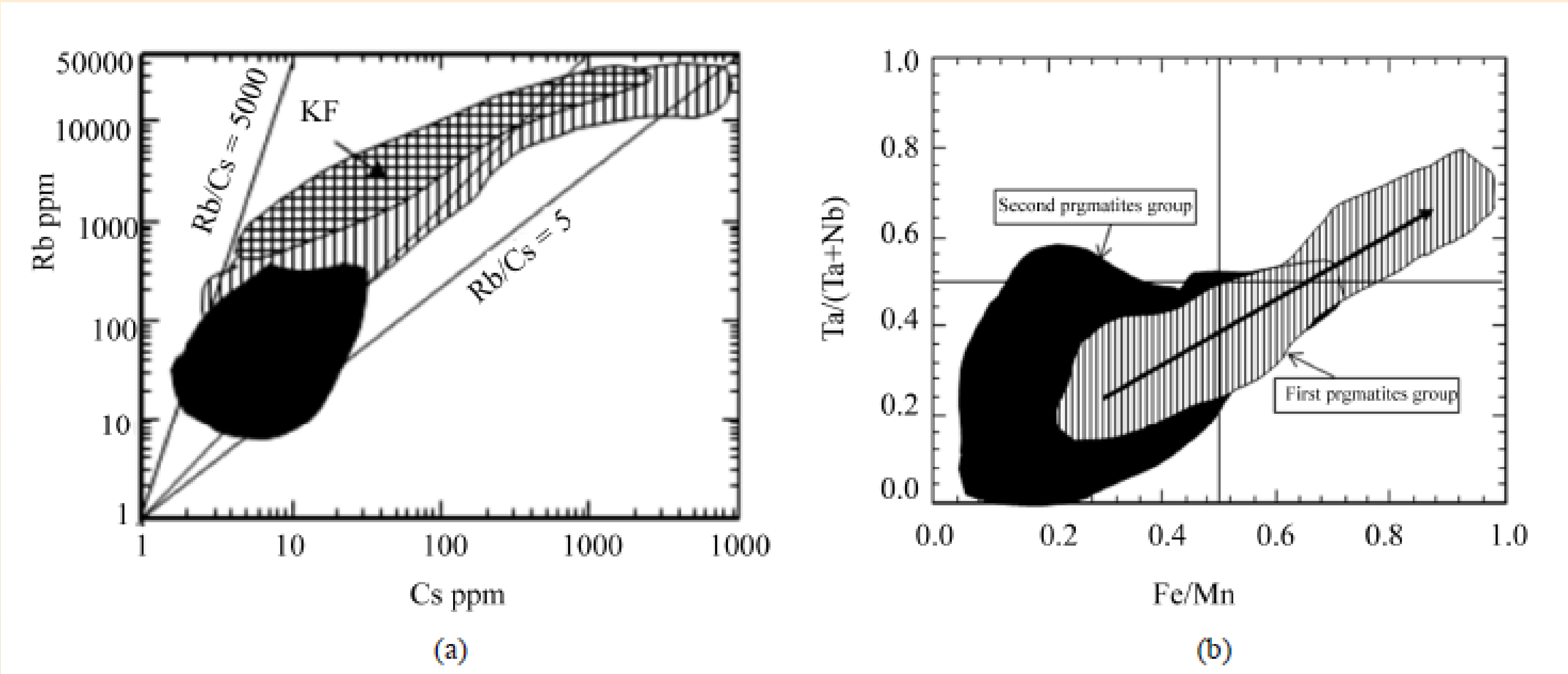
**Table 1. Main characteristics of the first group Pegmatites [3].**

| Zone | Mineralogy |
|---|---|
| Beryl pegmatite | Quartz, K-feldspar, biotite, muscovite, tourmaline, albite, garnet, beryl, columbite-tantalite (Nb > Ta). |
| Beryl Spodumene Pegmatite | Quartz, K-feldspar, muscovite, Li - mica, albite, tourmaline gem quality (**Figure 2**), behierit, mica, beryl, spodumene, amblygonite, columbite-tantalite (Nb = Ta), cassiterite and the apatite. |
| Spodumene Pegmatite | Quartz, K-feldspar, muscovite, Li-mica, albite, Elbaite, Behierit, garnet, (blue and pink) beryl, spodumene, amblygonite, columbite-tantalite (Nb < Ta), triphyllite, ferrisiklerite, heterosite, cassiterite and the apatite. |

**Table 2. Main characteristics of the second group [3].**

| Zone | Mineralogy |
|---|---|
| Contact | Quartz, biotite, K-feldspar, muscovite, albite, fluorite, garnet (almandine-spessartine) |
| Wall | Graphics Quartz, K-feldspar, muscovite, beryl, apatite, monazite (Ce), columbite-tantalite |
| Intermediary zone | K-Feldspar, Muscovite, Quartz. |
| core | Quartz |
| Metasomatic zone | Amazonite, beryl (construction or pink), cleavelandite (albite), apatite, phosphates (25 minerals), fluorite, columbite-tantalite ((Fe, Mn) $Nb_2O_6$), euxenite (Y) ((Y, Ca, Ce, U, Th) $(Nb, Ta, Ti)_2O_6$), Topaz, samarskite ((Fe, Y, U, REE) $(Nb, Ta)O_4$), autunite ((Ca $(UO_2)_2(PO_4)_2$) Microlite ($(Ca, Na)_2Ta_2O_6$ (O, OH, F)), Wulfenite ($PbMoO_4$), bismuthinite ($Bi_2S_3$), huttonite ($ThSiO_4$) and Kerala ((Ca, Ce, Th) $(P, Si)O_4$) |

Bilal et al. (2012)




A systematic compositional trend seems to suggest a petrogenetic link between the pegmatites of the region.

Bilal et al. (2012)

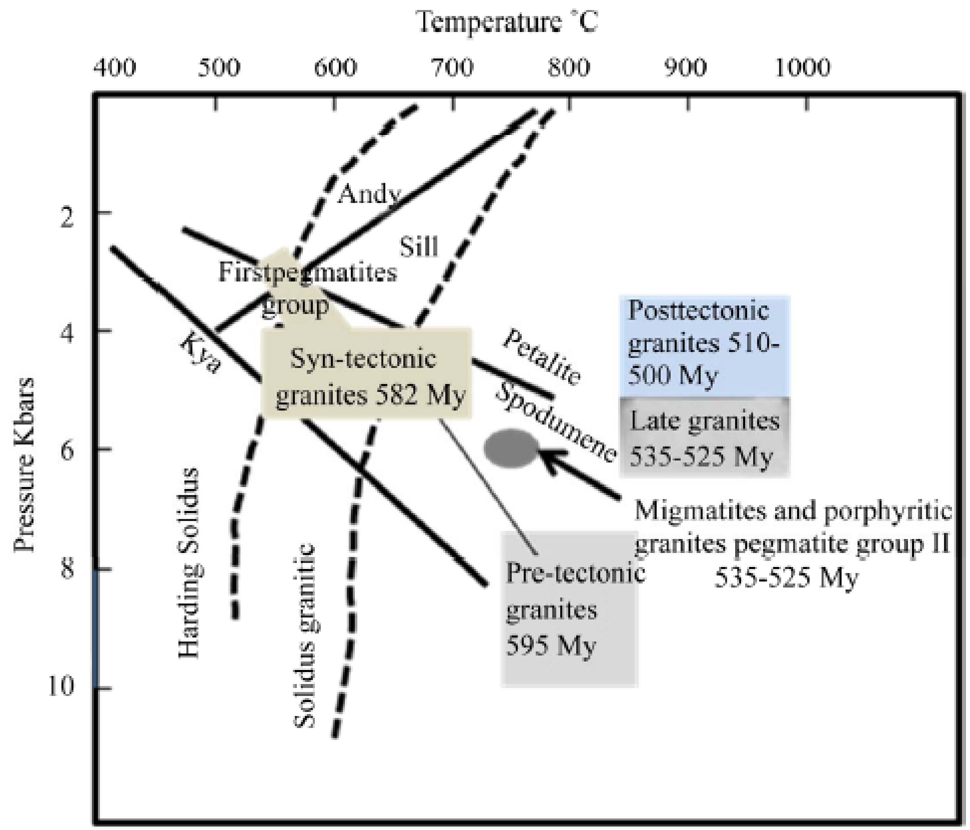



**Figure 8. Compilation of the P-T-t Neoproterozoic granites of the Minas Gerais [2,5]. The pre-tectonic granites (595 My) are exhumed during a main deformation phase D1 (590 - 565 My) corresponding to a collisional event. The sin-tectonic and the P-Li-Be bearing pegmatites have an age of 582My. The late and post-tectonic granitoids and the 2$^{nd}$ pegmatites group (537 – 520 My) are contemporaneous with the second phase of deformation D2 that corresponds to extensional movements. The post-tectonic granitoids were emplaced in the upper crust, 511 to 500 My.**

Bilal et al. (2012)

*Figure 5. Heavy machinery is often required for hard-rock mining in Brazil. At the Golconda tourmaline mine, bulldozers are used to move the overburden and waste from the mine entrance.*

Minas Gerais, Brazil (Proctor, 1984)

| Class | Subclass | Type | Subtype | Family |
| --- | --- | --- | --- | --- |
| Abyssal | HREE | | | NYF |
| | LREE | | | |
| | U | | | NYF |
| | BBe | | | LCT |
| Muscovite | | | | |
| Muscovite–rare element | REE | | | NYF |
| | Li | | | LCT |
| Rare element | REE | allanite–monazite | | NYF |
| | | euxenite | | |
| | | gadolinite | | |
| | Li | beryl | beryl–columbite | LCT |
| | | | beryl–columbite–phosphate | |
| | | complex | spodumene | |
| | | | petalite | |
| | | | lepidolite | |
| | | | elbaite | |
| | | | amblygonite | |
| | | albite–spodumene | | |
| | | albite | | |
| Miarolitic | REE | topaz–beryl | | NYF |
| | | gadolinite–fergusonite | | |
| | Li | beryl–topaz | | LCT |
| | | spodumene | | |
| | | petalite | | |
| | | lepidolite | | |

**TABLE 1** The pegmatite classification scheme of Černý and Ercit (2005), modified to show the correlation between pegmatite classes and families. NYF = niobium–yttrium–fluorine family (green); LCT = lithium–cesium–tantalum family (yellow); HREE = heavy rare earth elements; LREE = light rare earth elements

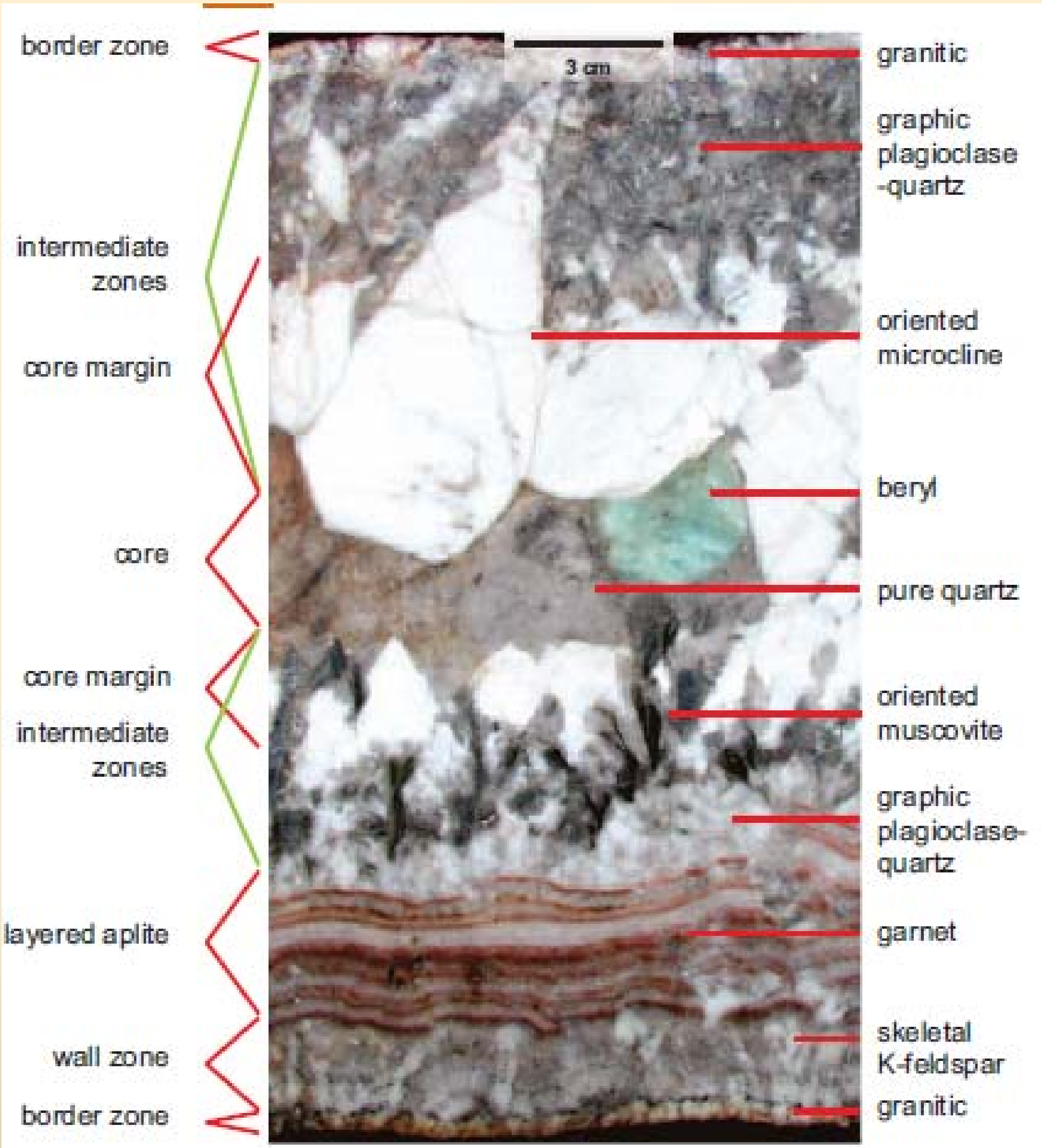



**FIGURE 4** Textural and zonal attributes of pegmatites. The image shows a complete section of a pegmatite dike, about 28 cm thick, located near Palomar Mountain, San Diego County, California (USA).

# London and Kontak (2012)

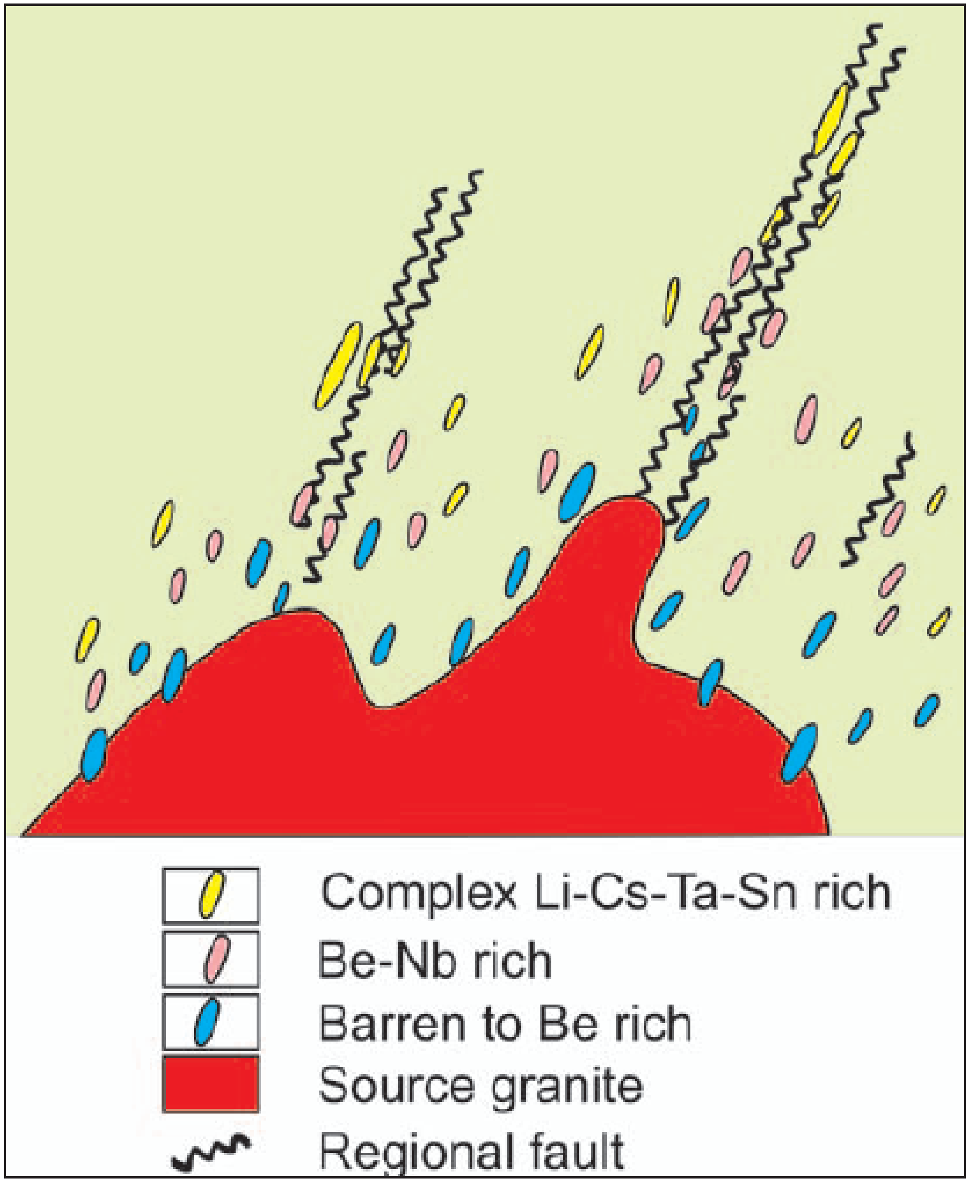


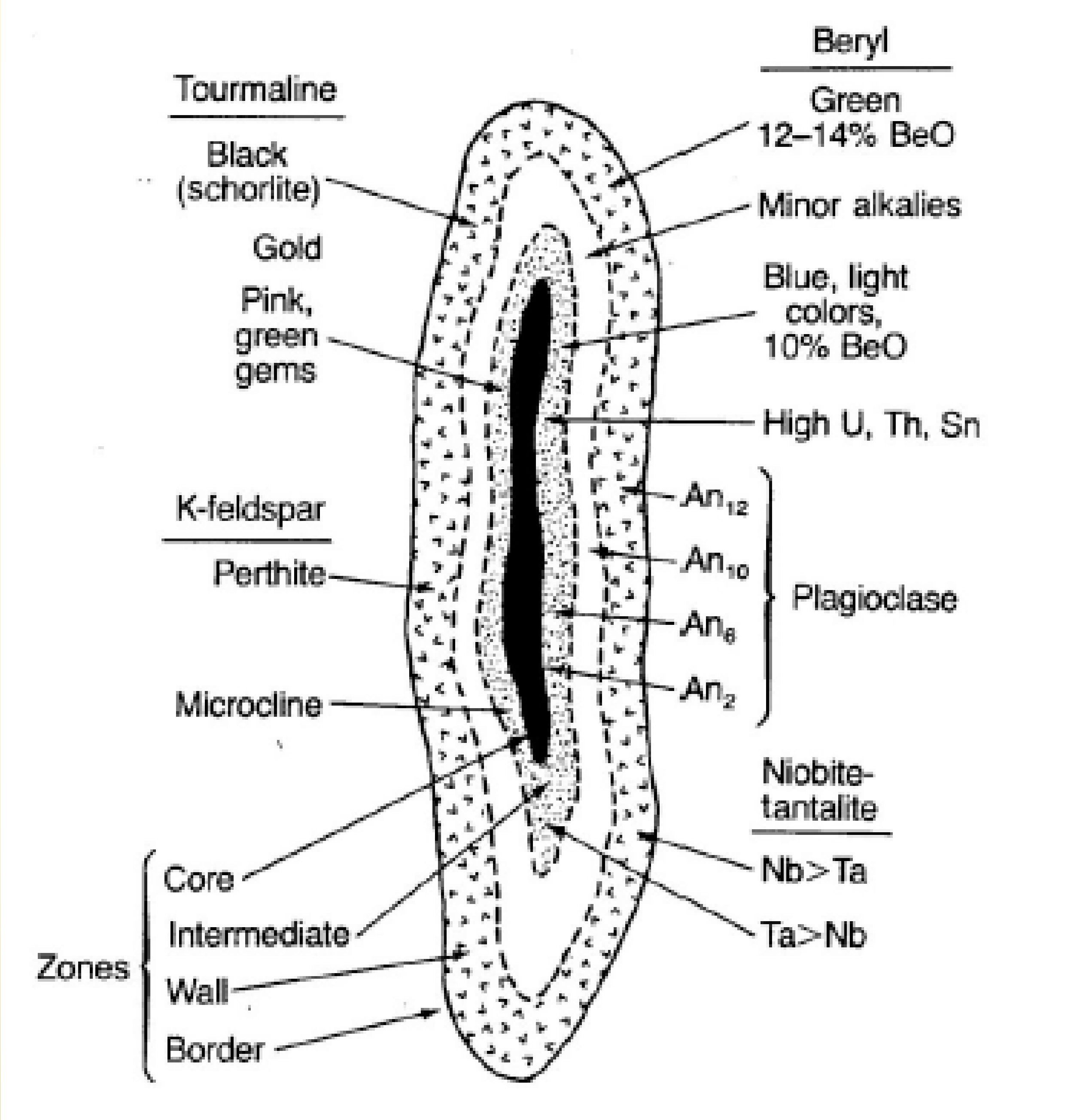

**Figure 1** Idealized zoned pegmatite field around a source granite. The maximum distance of pegmatites from the source granite is on the order of kilometers or, at most, tens of kilometers. Modified from Černý (1989)

# Stages

- Magmatic
  - Precipitation of feldspar and quartz, followed by other minerals
  - Formation of aqueous fluids
- Hydrothermal
  - Fluids ascend from the magma (decrease temperature, pressure)
  - Boiling
  - Volatiles enter vapor phase
  - Metals precipitate

# Zoning

- Unzoned or simple (quartz, feldspar, mica)
- Zoned or complex
  - Core (massive quartz, spodumene)
  - Intermediate (giant feldspar)
  - Wall (graphic texture, beryl, quartz, feldspar, mica, tourmalene)
  - Border (albite)



Tourmaline
Black (schorlite)
Gold
Pink, green gems
K-feldspar
Perthite
Microcline
Zones
Core
Intermediate
Wall
Border
Beryl
Green 12–14% BeO
Minor alkalies
Blue, light colors, 10% BeO
High U, Th, Sn
$An_{12}$
$An_{10}$
$An_6$
$An_2$
Plagioclase
Niobite-tantalite
Nb>Ta
Ta>Nb


# Jahns

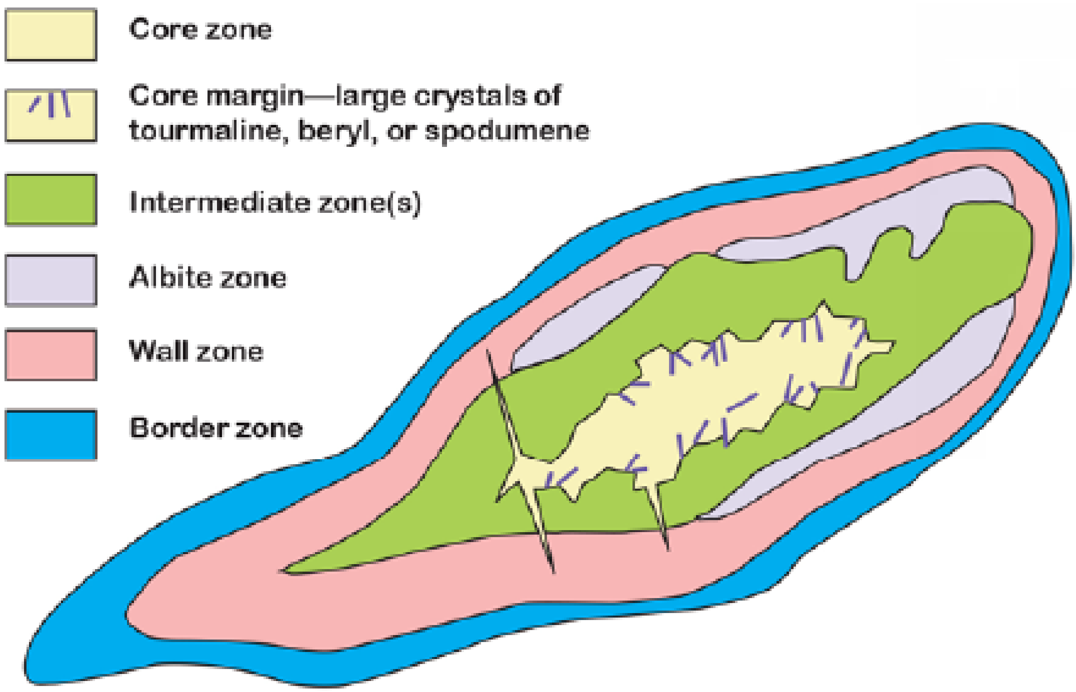



**Figure 2.** Deposit-scale zoning patterns in an idealized pegmatite, redrafted from Fetherston (2004) and Ĉerný (1991).

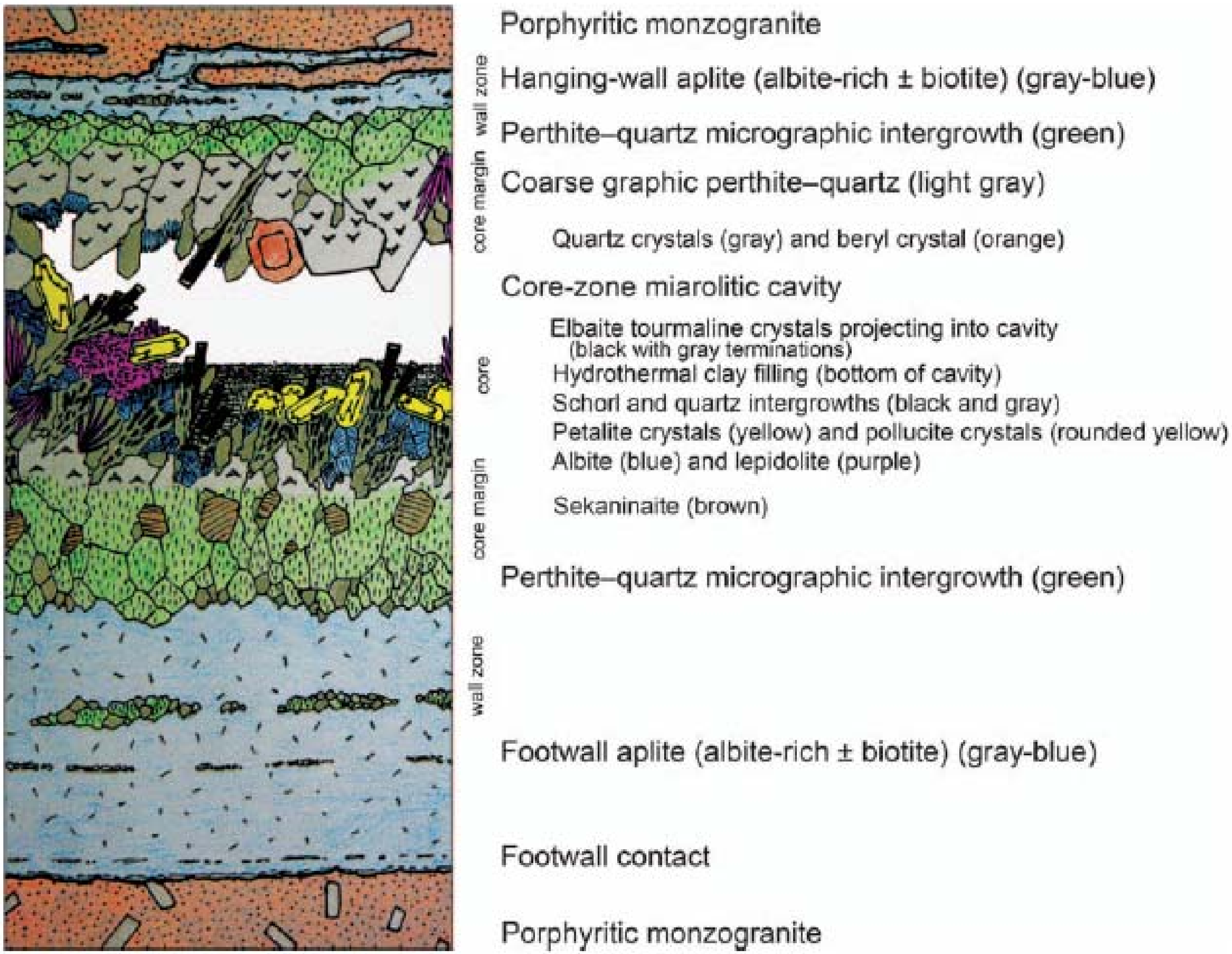



FIGURE 3 Idealized Elba pegmatite. DRAWING BY FEDERICO PEZZOTTA

Simmons et al., 2012

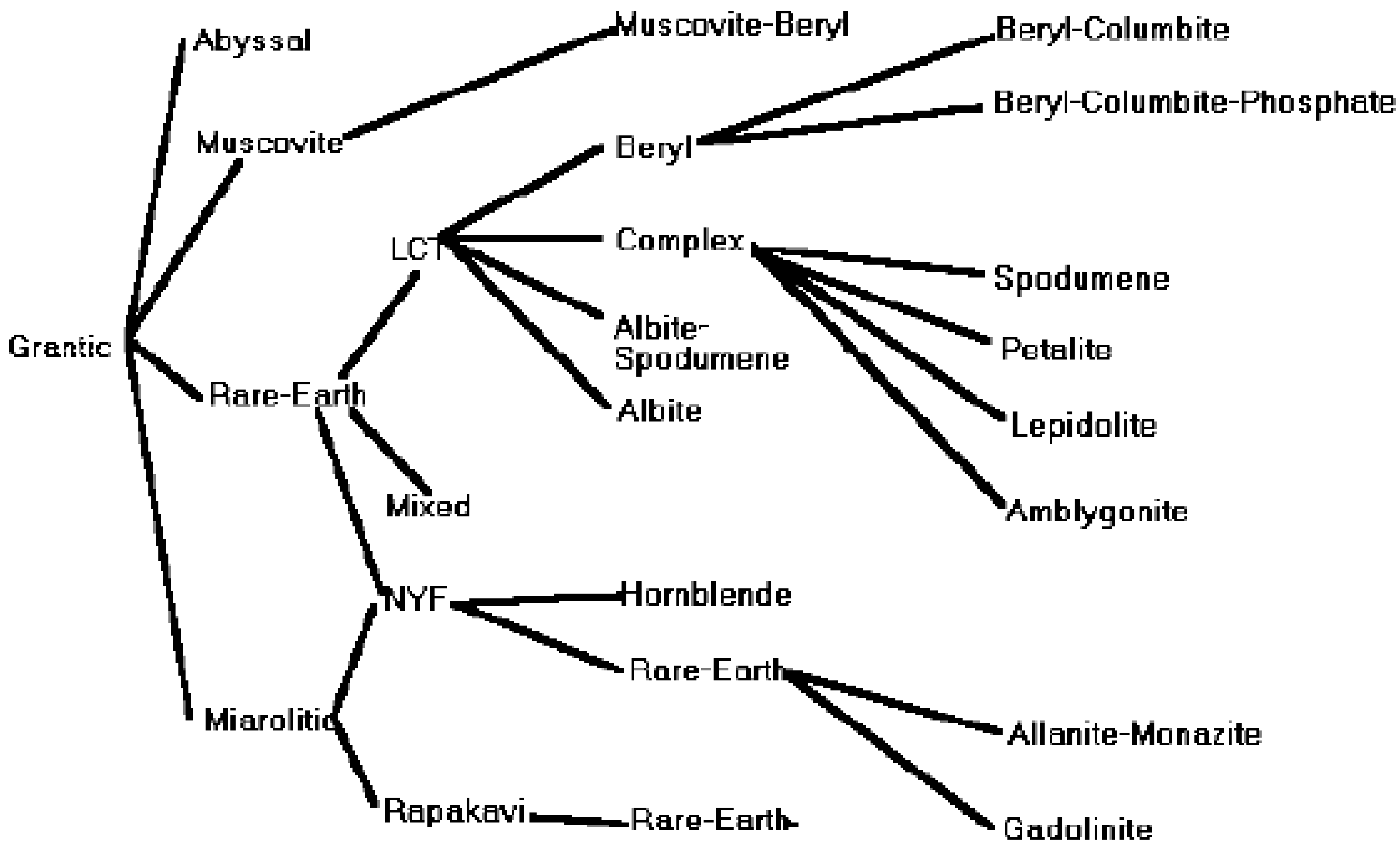
Table 2 The four classes of granitic pegmatites.

| Class | Family* | Typical Minor Elements | Metamorphic Environment | Relation to Granites | Structural Features | Examples |
|---|---|---|---|---|---|---|
| Abyssal | — | U,Th,Zr,Nb,Ti,Y, REE,Mo poor (to moderate) mineralization | (upper amphibolite to) low- to high-P granulite facies; ~4-9 kb, ~700-800°C | none (segregations of anatectic leucosome) | conformable to mobilized cross-cutting veins | Rae and Hearne Provinces, Sask. (Tremblay, 1978); Aldan and Anabar Shields, Siberia (Bushev and Koplus, 1980); Eastern Baltic Shield (Kalita, 1965) |
| Muscovite | — | Li,Be,Y,REE,Ti, U,Th,Nb>Ta poor (to moderate)** mineralization; micas and ceramic minerals | high-P, Barrovian amphibolite facies (kyanite-sillimanite); ~5-8 kb, ~650-580°C | none (anatectic bodies) to marginal and exterior | quasi-conformable to cross-cutting | White Sea region, USSR (Gorlov, 1975); Appalachian Province (Jahns *et al.*, 1952); Rajahstan, India (Shmakin, 1976) |
| Rare-element | LCT | Li,Rb,Cs,Be,Ga,Sn, Hf,Nb≷Ta,B,P,F poor to abundant mineralization; gemstock; industrial minerals | low-P, Abukuma amphibolite (to upper greenschist) facies (andalusite-sillimanite); ~2-4 kb, ~650-500°C | (interior to marginal to) exterior | quasi-conformable to cross-cutting | Yellowknife field, NWT (Meintzer, 1987); Black Hills, South Dakota (Shearer *et al.*, 1987); Cat Lake-Winnipeg River field, Manitoba (Černý *et al.*, 1981) |
| | NYF | Y,REE,Ti,U,Th,Zr, Nb>Ta,F; poor to abundant mineralization; ceramic minerals | variable | interior to marginal | interior pods, conformable to cross-cutting exterior bodies | Llano Co., Texas (Landes, 1932); South Platte district, Colorado (Simmons *et al.*, 1987); Western Keivy, Kola, USSR (Beus, 1960) |
| Miarolitic | NYF | Be,Y,REE,Ti,U,Th, Zr,Nb>Ta,F; poor mineralization; gemstock | shallow to sub-volcanic; ~1-2 kb | interior to marginal | interior pods and cross-cutting dykes | Pikes Peak, Colorado (Foord, 1982); Idaho (Boggs, 1986); Korosten pluton, Ukraine (Lazarenko *et al.*, 1973) |

***Notes***

* See Table 4 for explanation; ** Some Soviet authors distinguish a rare-element-muscovite class, in all respects intermediate between the muscovite and rare-element classes proper

# Pegmatite Classes




(Cerny 1992)

Table 21-2. Production/reserves of selected Canadian and foreign pegmatite deposits.

| Deposit | Production/reserves | Comments/references |
|---|---|---|
| *Canadian deposits* | | |
| Tanco mine, Manitoba | a) 1.9 Mt; 0.216% $Ta_2O_5$<br>b) 6.6 Mt; 2.76% $Li_2O$ (in spodumene + petalite)<br>c) 0.3 Mt; 23.3% $Cs_2O$<br>d) 0.8 Mt; 0.20% BeO | Reserves (Crouse et al., 1984) |
| Preissac-Lacorne area, Quebec | 19 Mt; 1.25% $Li_2O$ | Production plus reserves from the (former) Quebec Lithium property (Flanagan, 1978) |
| Fi (J.M.-Lit), Yellowknife district, N.W.T. | 13.9 Mt; 1.19% $Li_2O$ | "Identified paramarginal resources" (Lasmanis, 1978) |
| Thor (Echo), Yellowknife district, N.W.T. | 8.4 Mt; 1.5% $Li_2O$ | "Identified paramarginal resources" (Lasmanis, 1978) |
| Violet, Herb Lake area, Manitoba | 5.9 Mt; 1.2% $Li_2O$ | Reserves (Williams and Trueman, 1978) |
| Nama Creek, Georgia Lake area, Ontario | 3.9 Mt; 1.06% $Li_2O$ | Reserves, North and South zones (Pye, 1965) |
| Lac la Croix, Ontario | 1.4 Mt; 1.3% $Li_2O$ | Reserves (Mulligan, 1965) |
| Madawaska mine, (formerly Faraday mine), Bancroft district, Ontario | 4.5 Mt; 0.09% $U_3O_8$ | Production 1957-1964 and 1976-1982 (Carter and Colvine, 1985) |
| *Foreign deposits* | | |
| Tin-spodumene Belt, North Carolina | a) 26 Mt; 1.5% $Li_2O$<br>b) 30.5 Mt; 1.5% $Li_2O$ | Measured and indicated reserves, Kings Mountain, Foote Mineral Co. (Kunasz, 1982)<br>Reserves, Bessemer City, Lithium Corporation of America (Company news release, 1976) |
| Bikita, Zimbabwe | 10.8 Mt; 3.0% $Li_2O$ | Reserves (Wegener, 1981) |
| Kamativi, Zimbabwe | 100 Mt; 0.114% Sn, 0.603% $Li_2O$ | "Maximum inferrable reserves of a single pegmatite" (Bellasis and van der Heyde, 1962) |
| Uis, Namibia | 87 Mt; 0.134% Sn | Mineable plus possible reserves (Mining Magazine, November, 1983, p. 291) |
| Greenbushes, Australia | a) 28 Mt; 0.114% Sn, 0.043% $Ta_2O_5$, 0.031% $Nb_2O_5$<br>b) 33.5 Mt; 2.55% $Li_2O$ | Underground reserves (Knight and Wallace, 1982)<br>Proven and probable reserves (Knight, 1986) |
| Manono-Kitotolo, Zaire | 35 Mt; 1.3% $Li_2O$ | Reserves proved by systematic exploration (Evans, 1978) |
| Minas Gerais and Ceara states, Brazil | 106 Mt; 0.04% BeO | Estimated in situ ore (Soja and Sabin, 1986) |

Sinclair, 1996

TYPE 21

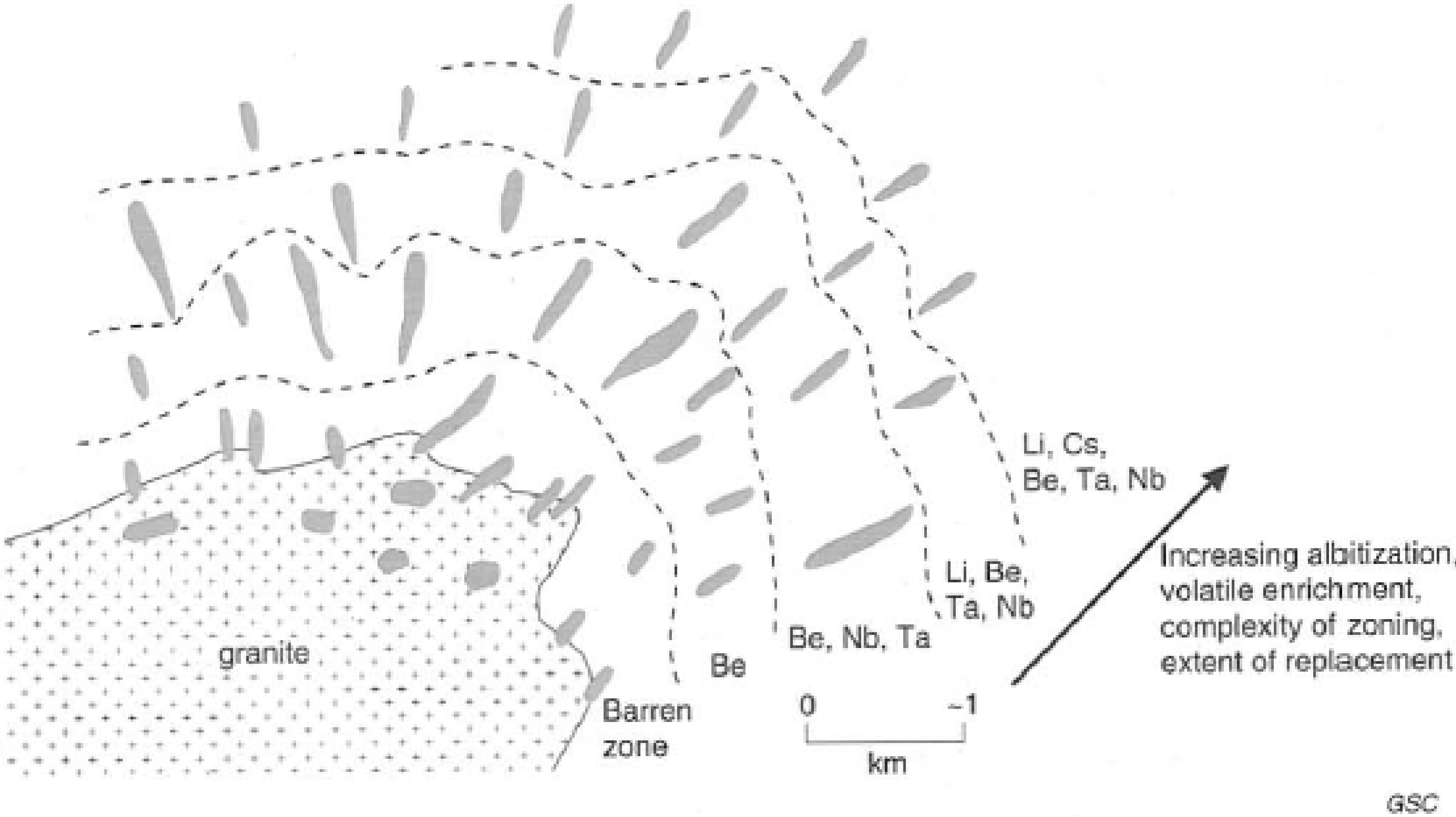



**Figure 21-4.** Schematic representation of the regional zonation of pegmatites (red) around a granite intrusion (modified from Trueman and Černý, 1982).

Sinclair, 1996

**Table 21-2.** Production/reserves of selected Canadian and foreign pegmatite deposits.

| Deposit | Production/reserves | Comments/references |
|---|---|---|
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| Tanco mine, Manitoba | a) 1.9 Mt; 0.216% $Ta_2O_5$<br>b) 6.6 Mt; 2.76% $Li_2O$ (in spodumene + petalite)<br>c) 0.3 Mt; 23.3% $Cs_2O$<br>d) 0.8 Mt; 0.20% BeO | Reserves (Crouse et al., 1984) |
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Sinclair, 1996

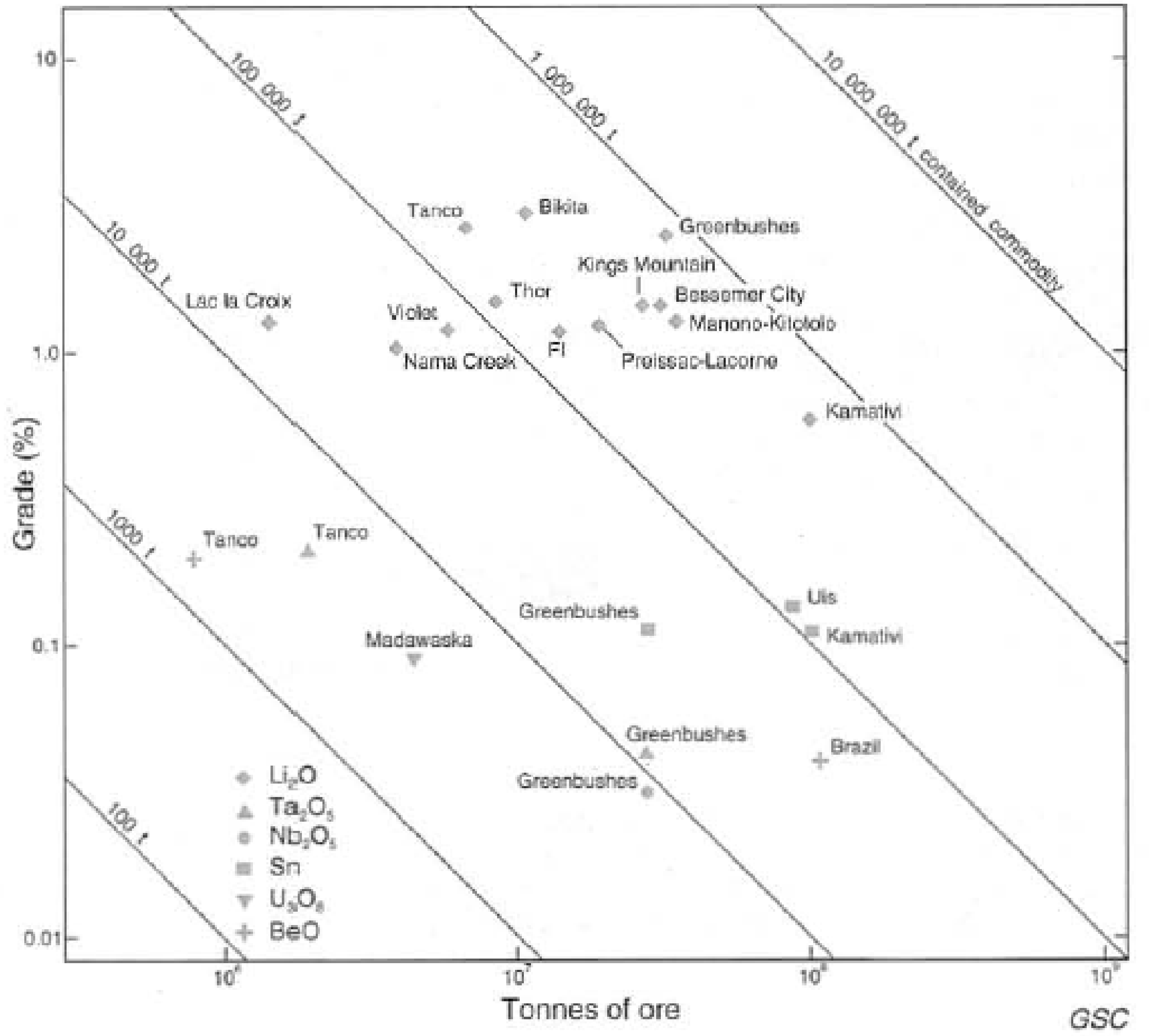
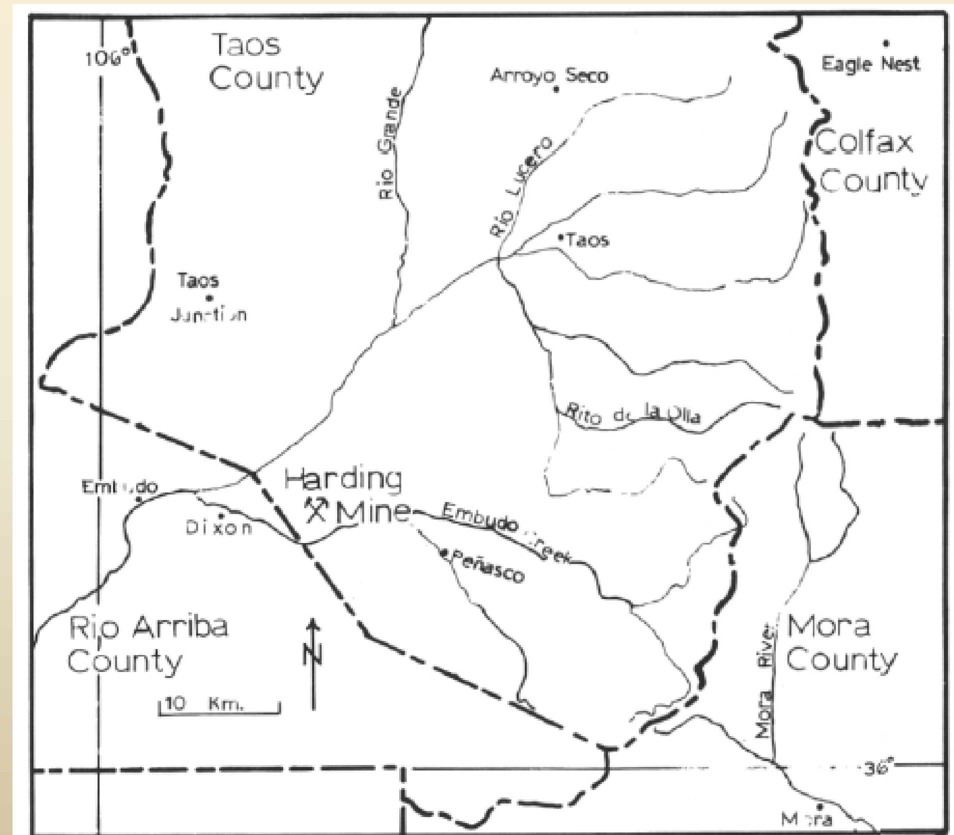



**Figure 21-2.** Grade versus tonnage diagram for pegmatite deposits (data are from Table 21-2).

Sinclair, 1996

# Harding Mine, New Mexico

- Discovered 1910
- Lepidolite mining 1919-1930
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5% $LiO_2$
- Microlite 1942-1947
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5% $LiO_2$
- Beryl 1950-1959
  - 12,000 tons of lepidolite-spodumene ore, averaging 3.5% $LiO_2$



# Harding mine, New Mexico

Sorting beryl-from left to right: Art Montgomery, Faudio Griego, A. E. Archuleta, Juan Romero, Eliseo Geigo and Pablo Rendo. (Laura Gilpin, 1953)

"Dumping" a small car-load of beryl ore down the chute to sorting platform. (Laura Gilpin, 1953)

Drilling deep underground in bery stope. (Laura Gilpin, 1953)

# Harding Mine

- BIOTITE + MUSCOVITE + QUARTZ ± GARNET ± MARGARITE ± SCHORL
- QUARTZ + ALBITE + MUSCOVITE ± PERTHITE
- QUARTZ ± ALBITE ± MUSCOVITE
- QUARTZ + LATH SPODUMENE
- MICROCLINE + SPODUMENE + LEPIDOLITE + ALBITE + MUSCOVITE + QUARTZ
- CLEAVELANDITE + ROSE MUSCOVITE ± QUARTZ
- CLEAVELANDITE + QUARTZ ± MUSCOVITE
- BLOCKY PERTHITE ± QUARTZ ± ALBITE
- QUARTZ + APLITIC ALBITE ± MUSCOVITE

# Be in Coal in NM

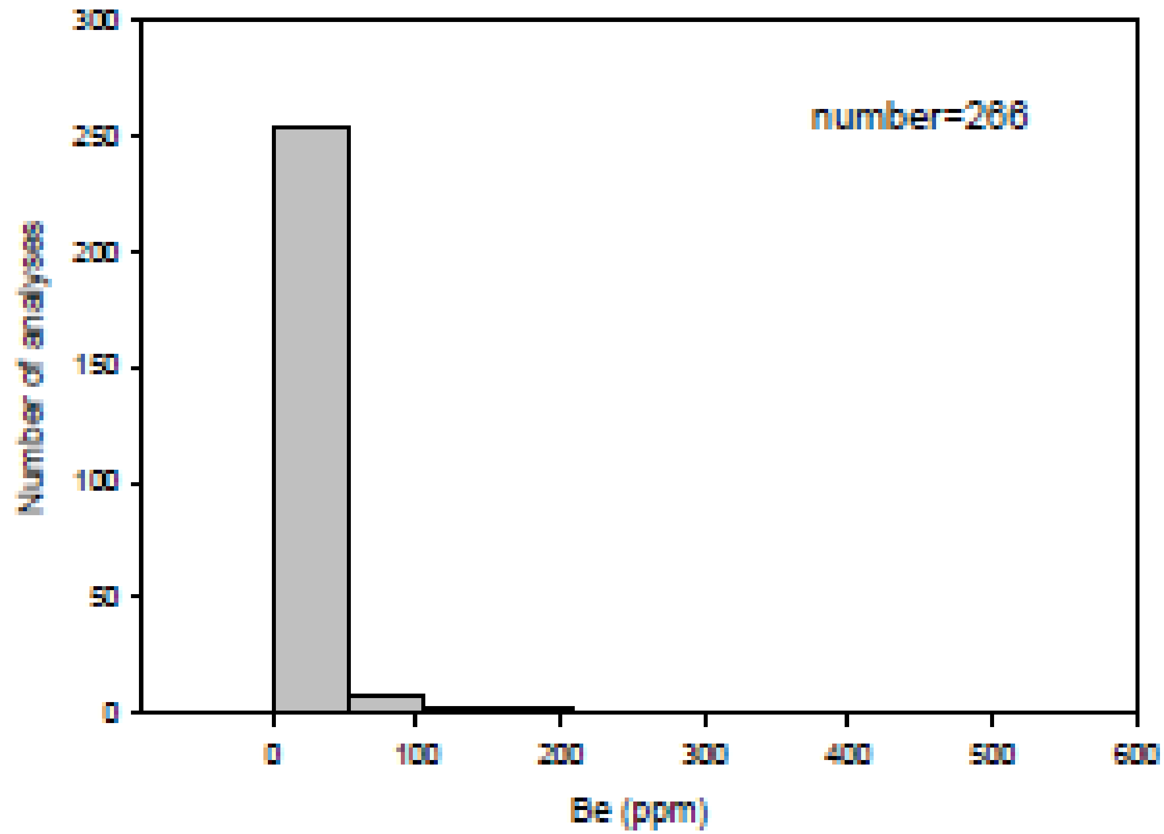
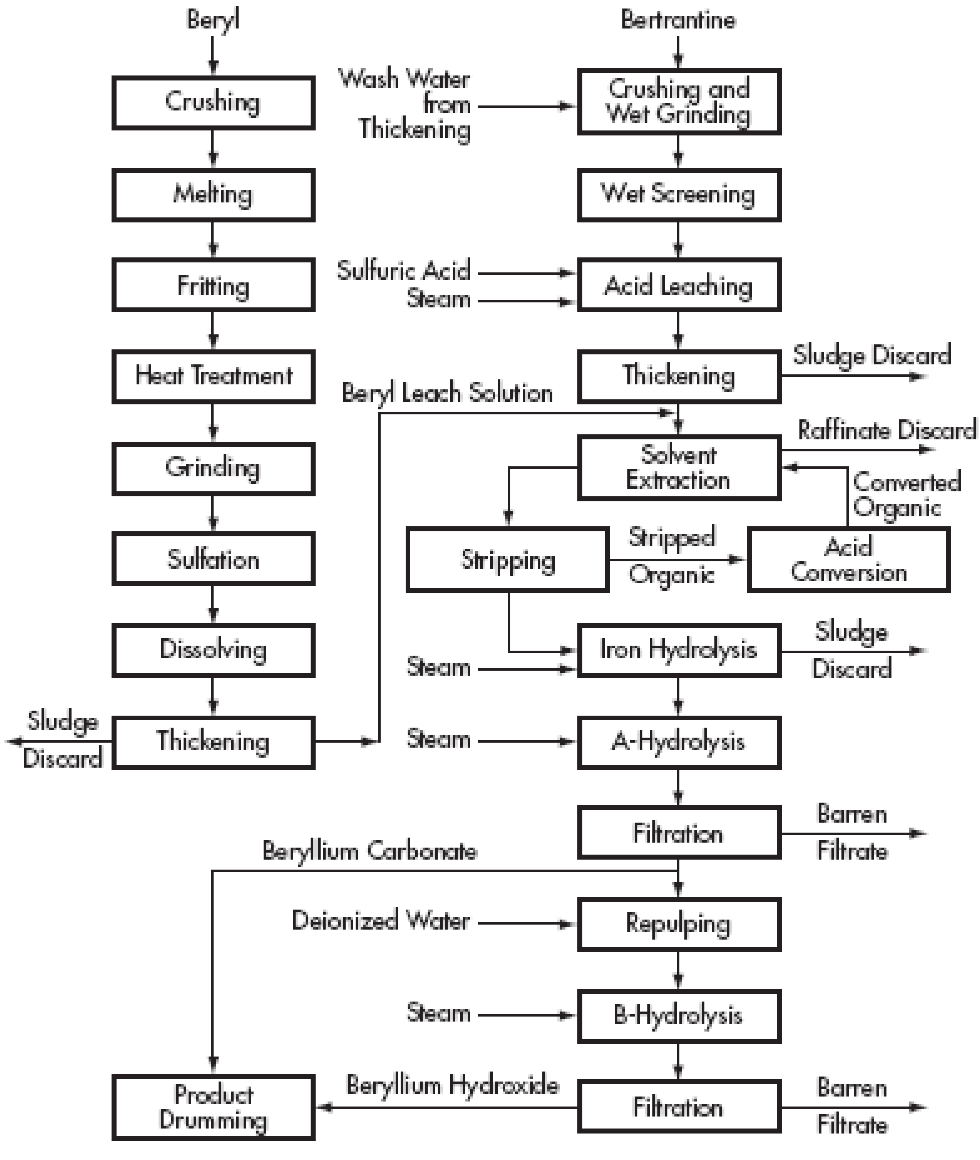



FIGURE 32. Beryllium analyses in coal samples (Hoffman, 1991).

# Beryllium—Processing

- Similar to Al, therefore it is not simple to separate
- maintain careful control over the quantity of beryllium dust and fumes in the workplace
- Mined, crushed, melted, solidified, treated with sulfuric acid to form a sulfate
- Be sulfate undergoes a series of chemical extraction steps resulting in pure Be hydroxide

# Processing




Courtesy of Brush Resources Inc.

**Figure 1. Beryllium hydroxide production from bertrandite and beryl**

# Beryllium—Health risks

- Toxic metal
  - Chronic beryllium disease, or CBD, is an inflammation in the lungs
- radioactive

# ASSIGNMENT

- **NEXT WEEK (Feb 26) no class, REE March 5, 12**
- **Midterm due March 19, 2013 by e-mail ginger@nmbg.nmt.edu**
- Castor, S.B., 2008, The Mountain Pass rare-earth carbonatite and associated ultrapotassic rocks, California: The Canadian Mineralogist, v. 46, p. 779-806, http://canmin.geoscienceworld.org/content/46/4/779.full.pdf+html?sid=180ae325-acd5-4226-9a02-175f7a865e17
- Long, K.R., van Gosen, B.S., Foley, N.K. and Cordier, D., 2010, The principle rare earth elements deposits of the United States—A summary of domestic deposits and a global perspective: U.S. Geological Survey, Scientific Investigations Report 2010-5220, 104 p., http://pubs.usgs.gov/sir/2010/5220/ (accessed 5/1/12).
- Mariano and Mariano, 2012, Rare earth mining and exploration in North America: Elements, v. 8, 369-376, http://elements.geoscienceworld.org/content/8/5/369.full.pdf+html?sid=605ebd04-9070-4994-9bce-b1cdd79f349d